

FINAL REPORT

For

ANALYSIS OF AURORAL PARTICLE FLUXES

June 1, 1972

Contract Number NASw 2212

Prepared by

C. R. Chappell

Lockheed Palo Alto Research Laboratory  
3251 Hanover Street  
Palo Alto, California 94304

For

National Aeronautics and Space Administration

Washington, D. C. 20546

(NASA-CR-127783) ANALYSIS OF AURORAL  
PARTICLE FLUXES Final Report C.R.  
Chappell (Lockheed Missiles and Space Co.)  
1 Jun. 1972 63 p  
CSCL 04A  
N72-29282

G3/13  
Unclas  
15967



## CONTENTS

Introduction . . . . .	1
Accomplishments . . . . .	2
Scientific Results . . . . .	4
Program for Next Year . . . . .	4
New Technology . . . . .	5
Conclusions . . . . .	5

## INTRODUCTION

Three Javelin rocket flights from Fort Churchill, Canada have provided detailed data on electron and proton precipitation in different types of auroral forms. These rockets named TWINS 1, TWINS 2, and  $p/\alpha$  were launched in 1967 and 1968. A thorough understanding of auroral phenomena requires a high time resolution study of electron and proton energy spectra and pitch angle distributions with the ability to separate spatial and temporal effects. The TWINS 1 and 2 data furnish this necessary information and in addition study such things as the characteristics of the backscattered electrons and the transit times of the different energy auroral particles. These transit times give a measurement of the auroral source distance. Analysis of these data have given a greater insight into the details of the physics of the auroral phenomenon.

## ACCOMPLISHMENTS

The analysis of the TWINS 1 and 2 rocket data began with the writing of a program to decommutate the SPECS data and to sort the data according to energy and pitch angle. Also the TWINS trajectory information given by the radar tracking measurements was combined with the McIlwain BIL program to calculate the values of the magnetic field B and the L-parameter along the flight path.

The next step in the data analysis was the calculation of the instrument geometric factors. This was done through a combination of the original calibration data from Rice University with  $\text{Ni}^{63}$  spectral measurements made at Lockheed during October of 1971. The measurements made at Lockheed compared the  $\text{Ni}^{63}$  sources used to calibrate the instruments at Rice with a Lockheed  $\text{Ni}^{63}$  source having a known spectrum. Once the geometric factors were derived from the calibration data, they were then used to convert the instrument count rates to absolute fluxes.

For purposes of data analysis, we desired the capability of viewing electron spectra at any selected time in the flight, and of viewing the pitch angle variations of the electron spectra. To that end, the rather limited decommutation program written initially was expanded to a general purpose computer program which generated electron spectra plots and pitch-angle distribution plots at all electron energies. The investment of time required to develop this capability proved to be well justified, for we

found it necessary to examine large quantities of the flight data in rather fine detail just to clarify and solidify our impressions of the general behavior of the electron precipitation in a complex auroral situation.

With the data reduced to a workable format, we were able to conduct an extensive analysis including the study of the variation of the incident electron energy spectra and pitch angle distributions throughout the flight, the study of the backscattered electron spectra and pitch angle distributions, and a detailed comparison of the measured and calculated backscattered spectra with regard to the physical processes involved in the interaction of auroral electrons with the atmosphere. This work is discussed in more detail in the enclosed reprints.

Work on the TWINS data to date has resulted in two J.G.R. articles, one which has already been published entitled "Measurements of Highly Collimated Short-Duration Bursts of Auroral Electrons and Comparison with Existing Auroral Models" by O'Brien and Reasoner, and a second which has been submitted to J.G.R. entitled "TWIN Payload Observations of Incident and Backscattered Auroral Electrons." Also, a talk entitled "TWIN Payload Observations of Precipitated and Backscattered Auroral Electrons" was presented at the 1972 spring meeting of the American Geophysical Union by Chappell, Reasoner, and O'Brien.

## SCIENTIFIC RESULTS

The TWINS data have revealed several surprising and interesting features of the auroral processes. These features include the measurement of highly collimated bursts of auroral electrons, very high  $\sim 100\%$  backscatter ratio of electrons below 1 keV in auroral arcs, and the presence of the "continuum" background spectrum in the auroral region which has peaks in energy superimposed upon it. The peak is seen to shift in energy as the payloads move into and out of the arc regions. The TWIN payload capability of the TWINS was also able to show the motion of the auroral particle precipitation region which corresponds to the motion of the arcs themselves. It is thought that the TWIN 2 observations are probably the first established observation of the same arc at two distinct times during one rocket flight. The detailed results and conclusions of the scientific analysis during the first year of the contract are presented in the two enclosed preprints of the J.G.R. articles.

## PROGRAM FOR NEXT YEAR

The analysis of the TWINS data will be continued under a follow-on contract to the present NASW-2212. The future work will carry on the detailed analysis of both the TWINS data and the other pertinent satellite data which bears on the overall problem of auroral and magnetospheric dynamics.

## NEW TECHNOLOGY

The instruments discussed here were developed under previous NASA grants. Consequently there has been no new technology developed under this contract.

## CONCLUSIONS

This work has produced more data on the complexity of the auroral phenomenon. The details of this complexity are discussed in the enclosed publications. The complicated nature of the auroral processes is evident both in the high space-time variability and complexity of the incident auroral particle spectra and in the unexpected variation of the backscattered particle spectra with energy. Further studies of these data during the coming year will give even more information on these processes.

TWIN PAYLOAD OBSERVATIONS OF  
INCIDENT AND BACKSCATTERED AURORAL ELECTRONS

D. L. Reasoner\* and C. R. Chappell  
Lockheed Palo Alto Research Laboratory  
3251 Hanover Street  
Palo Alto, California 94304

B. J. O'Brien  
Department of Environmental Protection  
Perth, Australia

June 1972

\*Permanent Address: Department of Space Science  
Rice University  
Houston, Texas 77001



TWIN PAYLOAD OBSERVATIONS OF  
INCIDENT AND BACKSCATTERED AURORAL ELECTRONS

ABSTRACT

Energy spectra and pitch angle distributions of auroral electrons have been measured in a pre-midnight multiple arc auroral display by a Javelin rocket containing two identical payloads which separated in flight. The rocket (code-named TWINS II) was launched from Fort Churchill, Canada at 0459 GMT on March 2, 1968, and covered an altitude range up to 800 km. The electron energy spectra between 40 eV and 20 keV show a "continuum" spectrum with a superimposed energetic peak. The center energy of the peak was observed to shift from 10 - 12 keV over the arcs to 2 - 3 keV between the arcs. This spectral structure is shown to be similar to the inverted "V" structure reported by other investigators. The inflight separation of the two payloads allowed investigation of spatial vs. temporal effects in the auroral precipitation. In one interval of the flight an arc was observed to be moving northward with a velocity of 0.6 km./sec. Calculated backscattered spectra are compared with those actually measured. Good agreement was observed for electron energies above about 1.5 keV, but below this energy the backscatter ratio was observed to be  $\sim 100\%$ . Several explanations for this unusually high ratio are considered, and a likely possibility is shown to be a parallel, downward-directed electric field between  $\sim 150$  and 500 km.

## INTRODUCTION

Measurements of auroral particle fluxes, their spectra and pitch-angle distributions have been the object of numerous satellite and rocket investigations. An excellent review of pertinent measurements has been given by Paulikas (1971).

The general features of auroral particle precipitation are now well-known, although the details of the origins of the particles and of their interaction with the atmosphere are far from understood. Several investigators have reported "anomalous" results in measurements of auroral particles. For example, Moser and Bruston (1966a,b) reported energetic protons traveling upward from mirror points well within the atmosphere and anti-correlations between electron and proton fluxes. A recent study by Reme and Bosqued (1971) reported observations of anti-correlated proton and electron fluxes and proton pitch angle distributions peaked along field lines. These observations were interpreted as indicating the presence of electric fields parallel to magnetic field lines in the upper ionosphere with magnitudes ranging up to a few hundred millivolts/meter. Furthermore, Moser and Bruston (1967) reported direct experimental evidence by means of rocket-borne electric field probes of such parallel electric fields in the upper ionosphere.

Choy and Arnoldy, (1971) have observed an anomalously high reflection coefficient, or backscatter ratio for auroral electrons. With energies

below 1 keV. These results are indeed surprising in view of the relatively low altitude of the measurements ( $< 150$  km., R. L. Arnoldy, private communication).

Chappell (1968) has compared, calculated and measured auroral electron backscatter ratios using data from the TWINS-I twin-payload sounding rocket (Westerlund, 1969.) The theoretical backscatter fluxes were calculated by means of a Fokker-Planck treatment of atmospheric Coulomb scattering. Discrepancies between calculated and measured backscatter were suggestive of atmospheric heating, a parallel electric field below the rocket, or a combination of both effects.

In this paper we report observations of precipitating ( $30^\circ < \alpha < 60^\circ$ ) and backscattered ( $120^\circ < \alpha < 150^\circ$ ) auroral electron fluxes in the energy range 40 ev - 20 kev over a series of IBC-2 auroral arcs. The measurements were made with the TWINS II payloads, a pair of identical payloads which were launched on an Argo D-4 Javelin sounding rocket and were separated in flight. Five distinct regions of particle precipitation are identified in terms of total energy input, and differing particle spectra characteristics are shown for each region. Variations in spectra near the edge of an arc are shown to resemble the "inverted V" spectral structure (Frank and Ackerson, 1971). Finally, measured and calculated backscatter spectra are compared and an attempt is made to explain the observed discrepancies.

## DESCRIPTION OF THE EXPERIMENT

A detailed description of the TWINS-II sounding rocket experiment and the auroral conditions at launch may be found in O'Brien and Reasoner (1971). Briefly, the payloads were launched from Fort Churchill, Canada on March 2, 1968 at 0459 U.T. into an IBC-II northward-moving multiple arc structure. The ground magnetometers recorded a 100  $\gamma$  negative bay at the time of the flight.

The rocket carried two identical payloads, TWINS 2A and TWINS 2B, which were separated in flight with a relative velocity along the flight direction at separation of approximately 4 meters/second. The relative and absolute velocities perpendicular to the magnetic field lines were  $1 \pm 0.2$  meters/second and  $585 \pm 6$  meters/second respectively. The flight azimuth was  $37^\circ$  east of true north. Auroral electron spectra were measured over an altitude range of 200 - 800 kilometers, and the payloads covered L - values from  $L \cong 9$  to  $L \cong 13$ .

Each payload carried identical detector complements, consisting of two wide-range electron spectrometers, three fixed-energy differential electron detectors, and a large-area geiger tube. Of relevance to this study were the two electron spectrometers, code-named SPECS (O'Brien, et al, 1967). The SPECS detectors were electrostatic deflection spectrometers employing channel electron multipliers and were sensitive to electrons with  $40 \text{ ev} < E < 20 \text{ kev}$ . The upward-looking SPECS scanned a pitch angle range

of  $30^\circ$  to  $60^\circ$  in  $\sim 5^\circ$  increments and the downward-looking SPECS simultaneously scanned a range of  $120^\circ$  to  $150^\circ$ . The SPECS required 3.6 seconds to complete a measurement cycle of all electron energies. Payload aspect information was provided by a fluxgate magnetometer.

## EXPERIMENTAL RESULTS

An overview of the auroral conditions encountered during the TWINS II flight is best shown by a plot of the total energy deposited, obtained by integrating over the measured spectra. Figures 1 and 2 show the values of the directional electron energy deposited and backscattered as calculated from the measurements of TWINS 2A and 2B respectively for electron energies  $>400$  ev and pitch angles of  $30^\circ < \alpha < 60^\circ$  and  $120^\circ < \alpha < 150^\circ$ . The payloads encountered two distinct periods of enhanced precipitation at 240-350 seconds and again at 670-710 seconds. We can associate these periods of enhanced precipitation with the visible auroral arcs. The precipitated fluxes were isotropic to within a factor of 2-3 over the pitch angle range  $30^\circ < \alpha < 60^\circ$ , and we assume that the isotropy extended over the entire upper hemisphere. With this assumption the total energy deposited was therefore  $\sim 20$  ergs/cm<sup>2</sup>-sec. This agrees well with the photometrically measured brightness of the auroral forms at launch of 10-20 kilorayleighs.

The gross features of Figures 1 and 2 are in good agreement, as would be expected since the maximum payload separation was 700 meters. The

backscattered flux measured by TWINS 2A is apparently less than that measured by TWINS 2B, but this was due to a failure of two of the six channels of the downward-looking SPECS on TWINS 2A. Therefore a portion of the electron spectrum was not measured by this detector.

A closer examination of Figures 1 and 2 reveals that the decrease in precipitation at  $T = 350$  seconds was observed  $6 \pm 3$  seconds earlier by TWINS 2B (the following payload) than by TWINS 2A (the leading payload). This means that the arc observed from 250 - 350 seconds was moving northward more rapidly than the payloads and effectively overtook and ran ahead of them. Considering the payload absolute horizontal velocity of .585 km/sec and the separation at this time of 217 meters, the arc is calculated to be moving northward with a velocity along the payload flight direction ( $37^\circ$  east of north) of .61 km/sec. Flux enhancements later in the flight (e.g.  $T = 630$  seconds) do not display any time delays between detection by the two payloads, although the SPECS detectors with their 3.6 second cycle time would not have been able to resolve the time delay of  $\sim 2$  seconds expected if the payloads encountered a stationary or slowly-moving spatial structure. It is therefore possible that the payloads initially observed an arc moving northward which subsequently slowed and was again encountered by the northward-moving payloads. The unique capability of the TWINS payloads to distinguish temporal and spatial effects demonstrated above was also instrumental in the discovery of short-duration field-aligned electron bursts reported previously by O'Brien and Reasoner (1971).

The next series of figures (3 - 8) shows precipitated and backscattered electron spectra measured at various times in the flight by TWINS 2B. These spectra represent regions of differing precipitation intensity at  $T = 281, 414, 479, 630,$  and  $670$  seconds. These times are indicated by the arrows on Figure 2. Each spectrum represents an average over 3 SPECS cycles, or about 10 seconds and the periods were selected to insure that the data were stationary over the averaging period. Each point is an average of 147 samples of 10 milliseconds each.

Figure 3 shows the incident, or precipitated, spectrum at  $T = 281$  seconds. The fluxes in units of  $\text{electrons}/\text{cm}^2\text{-sec-stev-eV}$  are plotted as a function of electron energy in eV. This spectrum was measured at an altitude of 585 kilometers and represents pitch angles of  $32^\circ \rightarrow 56^\circ$ . The loss cone (referenced to the 100 km level) at 585 km is  $64^\circ$  and hence all of the observed incident electrons would theoretically mirror below 100 kilometers and thus be subject to severe atmospheric scattering and loss. All down-going electrons measured throughout the flight were in the loss cone; hence no information on the trapped particle population was acquired. The group of data points at each energy represent the spread in flux at a given energy for different pitch angles between  $32^\circ$  and  $56^\circ$  and indicate the variation of energy spectrum with pitch angle. This variation is a factor of 2 to 3 maximum. The error bars for the points are also indicated. The errors are dominated by uncertainties in the instrument calibration of  $\pm 20\%$ . Errors due to counting statistics are negligible, typically  $< 5\%$ .

The precipitating electrons shown in Figure 3 have a peak in the energy range of 6 - 17 keV which contains the bulk of the total precipitating energy.

Figure 4 shows the electron spectrum which was backscattered from the atmosphere below the payload as measured simultaneously at  $T = 281$  seconds by the downward-viewing SPECS. The data format is the same as for the previous figure. The pitch angle range measured was  $124^\circ$  to  $148^\circ$ . Note that the backscattered spectrum exhibits a small peak in the range 5 - 15 keV which is almost an order of magnitude lower in intensity than the precipitated flux.

As the payloads passed from the region of intense precipitation into one of intermediate precipitation ( $T = 414$  seconds), the spectra changed to those shown in Figure 5. Here we have shown only the sketched incident and backscattered spectra without including the data points showing the spread in pitch angle. This is done here and in subsequent presentations for the sake of brevity and to afford easier comparison of spectra.

The incident spectrum at  $T = 414$  (solid line) shows two peaks, a prominent peak in the range 2 - 9 keV and a less prominent one in the range 500 eV - 1.2 keV. Note that as the payloads passed out of the region of enhanced precipitation (Figure 3) the peak shifted down from 6 - 17 keV to 2 - 9 keV. The backscattered spectrum (dashed line) shows no evidence of a peak. Note also that the flux of backscattered electrons with  $E < 600$  eV is comparable to or greater than the corresponding flux of



precipitating electrons. We will comment further on this surprising backscatter ratio in a later section.

Figure 6 shows the incident and backscattered spectra in the region of low intensity precipitation at  $T = 479$  seconds. The peak in the incident spectrum has shifted to the energy range  $1.5 - 4$  keV and has diminished in differential flux level by a factor of 2 from the previous spectrum. This precipitated spectrum measured between the intense precipitation regions is similar to the background "continuum" discussed by Westerlund (1969) using data from TWINS I, a similar rocket payload fired one year earlier. Here, the backscattered spectrum shows no peak in energy, unlike the backscattered spectrum in the intense precipitation region ( $T = 281$  seconds, Figure 4). Again, the backscatter ratio is  $\sim 100\%$  for energies less than 500 eV.

Following the low intensity region, the rocket encountered another region of intermediate intensity precipitation with the incident electron energy spectrum showing a characteristic upward shift in the energy of the peak to the  $3 - 12$  keV range. Figure 7 shows representative spectra from this region measured at  $T = 630$  seconds. The backscattered spectrum has a slight peak in this same energy range. In this case the backscatter ratio is  $\sim 100\%$  for energies less than 1.2 keV.

Finally, the payloads again encountered a region of intense precipitation (Figure 8) at  $T = 670$  seconds. The energy of the peak is in the  $3 - 16$  keV range, and the incident spectrum is similar to that observed

during the first enhanced period at  $T = 281$  seconds. This adds support to the thesis advanced earlier that the two regions of intense precipitation were one and the same arc. The backscatter peak is again prominent, and the backscatter ratio is  $\sim 100\%$  for energies below 1 keV.

From this series of spectra it is clear that changes in the total energy deposited were caused by shifts in the energy of an energetic peak which appeared to be superimposed on a much more stable "continuum" spectrum. During this TWINS II flight, unlike the case in the TWINS I flight (Westerlund, 1969) the peak never completely disappeared although it was considerably diminished in both intensity and average energy in the period of  $T = 460$  to  $T = 500$  seconds.

A higher time resolution study of this peak shift effect is shown in Figure 9. Here three successive incident spectra at  $T = 351$ ,  $T = 366$ , and  $T = 405$  seconds are plotted to display the spectral change over the time period of a sharp decrease in total precipitating intensity (Figure 1). The shift of the energy of the peak to progressively lower values is clearly evident. We will discuss this further in a later section.

Perhaps the most surprising feature of these spectra is the very high,  $\sim 100\%$ , backscatter ratio for electron energies less than about 1 keV. The expected ratio computed from Coulomb scattering is usually on the order of 10%. In the following section we consider the backscatter phenomena in detail, presenting calculations of expected backscattered fluxes for comparison with those actually observed.

## COMPARISON OF EXPERIMENTAL AND THEORETICAL BACKSCATTER RESULTS

To examine the interaction of the precipitated auroral electrons with the atmosphere we have used the measured incident electron spectrum as input for a theoretical computer code which calculates the expected backscattered electron spectrum. This calculated backscattered spectrum can then be directly compared with the backscattered spectrum measured simultaneously by the downward-viewing SPECS detector on the TWINS payload. Any differences between the calculated and measured backscattered spectra can be interpreted in terms of the physical processes occurring in the interaction region.

The theoretical calculations were made using the Fokker-Planck diffusion equation solution of Walt, MacDonald, and Francis (1968). This treatment includes angular scattering, continuous energy loss, and the effect of a converging magnetic field. The solution is in the form of a distribution function for the auroral electrons as a function of energy, pitch angle, and altitude. The calculations were made using differential cross-sections given by the first Born approximation (Mott and Massey, 1965) and the continuous energy loss formula of Bethe (1933). These calculations are reasonably accurate ( $\pm 10\%$ ) for isotropic pitch angle distributions and for electron energies down to about 500 eV. The computations done in this work are carried down to 1 keV.

Figure 10 shows the measured incident (solid line) and backscattered (x's) spectra at  $T = 281$  in the first region of enhanced precipitation.

The incident spectrum which was assumed to be isotropic in pitch angle over the upper hemisphere was used as input to the backscatter code. The blue shaded area represents the calculated backscattered flux in the range of pitch angles of  $126^\circ \rightarrow 149^\circ$  corresponding to those pitch angles measured by the downward viewing SPECS. The agreement between the calculated backscattered flux and the measured flux (x's) is reasonably good above about 1.5 keV. However below 1.5 keV the measured backscattered fluxes are roughly equal in magnitude to the incident fluxes (backscatter ratio of  $\sim 100\%$ ). The theoretical calculations, which employ Coulomb scattering only, predict a backscatter ratio more on the order of 10-20%, not 100%. In other words, the electrons of energy below 1 - 2 keV in this enhanced precipitation region are either kept out of the atmosphere preventing any loss or the incident primary particles are replaced by secondaries produced in atmospheric scattering.

The most obvious explanation for the 100% backscatter below 1 - 2 keV is the presence of a parallel downward directed electric field above the atmosphere with a total potential drop of about 1 keV in magnitude. This field would prevent electrons of less than 1 keV from entering the atmosphere and would reflect them undiminished in flux value. Other potential explanations also exist for this unusually high backscatter ratio. The production of multiple secondary electrons in the atmosphere by the energetic precipitating primaries is a possibility. Also, a severe modulation of the magnetic field by the auroral electrojet currents could possibly affect the particle pitch angles and cause reflection. In anticipation of

the results of a later discussion on the relative merits of these possibilities, we will examine theoretically the effect of a parallel downward directed electric field of potential drop of 1 keV situated below the rocket and above the effective scattering layer of the neutral atmosphere. In this  $T = 281$  case, this field would be between 585 km and about 150 km.

For this  $T = 281$  case we have again used the measured incident spectrum shown in Figure 10 but have included a vertical potential drop of 1 keV just below the rocket. The effect of this parallel field is to alter the pitch angle distribution of the incident particles in such a way as to reflect particles whose energy component parallel to the field is less than 1 keV and to reduce the energy of particles which traverse the field region by 1 keV. The Coulomb scattering, energy loss, and mirroring of these penetrating electrons is then calculated by the computer code and the resulting backscattered spectrum is then transformed back through the potential drop with the corresponding change in pitch angle distribution and increase in energy. The results of this calculation are shown by the red shaded area in Figure 10 for energies down to 1 keV. Note that the effect of the field is to increase the flux backscattered at the more nearly perpendicular pitch angles for electrons between 1 and  $\sim 10$  keV in energy and also to cause the 100% backscatter below energies of a few keV. Qualitatively then, the calculations show that with the addition of a parallel downward directed electric field above the atmosphere to the general effects of coulomb scattering, the predicted backscattered flux is in good agreement with the measured backscattered flux for all energies.

Figure 11 shows the measured and calculated backscattered fluxes for the time period of very low intensity precipitation,  $T = 479$  seconds. As before the measured incident spectrum is shown by the solid line and is used as the input for the calculation. The shaded area shows the predicted range of backscattered flux for the pitch angles measured by the downward viewing SPECS. The measured backscattered electrons are again shown by the "x's." In this calculation we have not included a parallel electric field. One can see that the agreement above 1 keV for coulomb scattering is quite good. Recall that this set of spectra was measured between the auroral arc regions. Although no parallel electric field is required to obtain agreement between calculated and observed backscattered spectra above 1 keV in this low intensity precipitation region, one can see that below about 500 eV the backscattered flux again approximately equals the incident flux indicating the possible need for a lower magnitude parallel field of about 500 eV to give agreement.

Figure 12 shows the set of spectra representing the second payload encounter with the intense precipitation region at  $T = 670$  seconds. As above the shaded area represents the predicted backscattered fluxes with no parallel electric field and the "x's" represent the measured backscattered fluxes. As in the first case ( $T = 281$ ) the agreement at higher energies (greater than about 1.5 keV) is good. However as in the previous encounter with the intense precipitation region, the backscattered fluxes below about 1.5 keV are comparable to the incident fluxes in contrast to the predictions

of the Coulomb scattering calculations which show the backscattered flux decreasing with decreasing energy below 1.5 keV. As before one can see that the addition of a parallel electric field of about 1 keV total potential drop below the rocket would cause an increase in the predicted backscattered fluxes at lower energies (less than about 6 or 8 keV) with a backscattered flux equal to the incident flux below about 1.5 keV in agreement with the measured fluxes.

We have found then that in regions of auroral precipitation the measured backscattered electron fluxes agree quite well with the backscattered fluxes predicted from Coulomb scattering alone for the higher energies greater than about 1.5 keV. However, for the lower energies, agreement between predicted and measured backscattered fluxes for Coulomb scattering alone is not sufficient but requires an effect such as a parallel downward directed electric field between the rocket and the atmosphere with a total potential drop of about 1 keV in regions of intense precipitation and about 500 eV in regions of less intense precipitation.

## SUMMARY AND DISCUSSION

The features of the measured precipitated and backscattered auroral electron spectra can be summarized as follows:

- (1) The spectra contain two main components - a "continuum" spectrum which remains fairly stable throughout the flight and a peak in

the 6 - 17 keV range which is present over the auroral arcs but which shifts to lower energy and intensity as the payloads move away from the arc. This peak, when present, carries the bulk of the total energy deposited.

- (2) The incident electron fluxes at all energies appear to be isotropic in pitch angle to within a factor of 2 or 3 over the observed pitch angle range of  $30^\circ \rightarrow 60^\circ$ .
- (3) The backscattered fluxes for energies below about 1 keV appear to be isotropic within a factor of 2 or 3 and equal in intensity to the precipitated fluxes. Above about 1 keV the fluxes show a larger variation with pitch angle as expected from the effects of atmospheric scattering and the magnitude of the backscatter ratio ( $j(E)_{\text{up}}/J(E)_{\text{down}}$ ) at a given energy decreases with increasing energy.
- (4) A theoretical backscatter calculation employing Coulomb scattering, continuous energy loss and magnetic mirroring and using the measured incident spectrum as input is able to reproduce the measured backscattered spectrum for energies greater than 1 keV in intense regions of precipitation and for energies of greater than 500 eV in regions of less intense precipitation. The measured backscattered spectra below about 1 keV, however, cannot be explained on the basis of Coulomb scattering alone.



In (1) above we mentioned the shift in energy of the peak in the incident electron spectrum as the payloads move in and out of the auroral arc region. If this shift in peak energy were displayed on an energy-time spectrogram it would resemble an "inverted V" structure similar to that discussed by Frank and Ackerson (1971). The widths of the structures observed here (50-100 km) are in reasonable agreement with the "typical" widths of 200 km discussed by Frank and Ackerson (1971). Exact agreement on these widths is not expected due to uncertainties resulting from high velocities of the auroral forms relative to the rocket payload velocities.

The most interesting feature of the electron spectra is the 100% backscatter ratio for energies less than 1 keV. As we mentioned in the previous section, there are at least three possible explanations for this large ratio — secondary electrons which are produced by the high energy primary electrons and which are scattered upward out of the atmosphere, a large variation in the ambient magnetic field caused by the nearby auroral electrojet which changes the electron pitch angles, or a downward-directed parallel electric field with a potential drop of 1 keV above the atmosphere which reflects lower energy electrons before they undergo scattering.

We discount the possibility that secondary electrons are responsible for the upward fluxes at energies between 40 - 100 eV. If these particles were secondaries, we would expect that the measured upward flux of these particles would be correlated with the measured incident primary energy flux of the particles greater than 400 eV. In Figure 13 we show the incident energy

flux from Figure 1 along with the 40 eV precipitated and backscattered number flux. There is a good correlation between the 40 eV downgoing and upcoming flux, but there is no significant correlation between the precipitated primary energy flux and the 40 eV upcoming or backscattered flux. Thus, the experimental evidence argues against secondary electrons as a source of these low energy electrons.

Theoretical evidence also argues against secondaries as a source of the high intensity low energy upflux. Most of the secondaries that are produced are below 300 km and the photoelectron calculations of Nagy and Banks (1970) show that these electrons cannot escape the atmosphere because of the very high degree of scattering. However, these same calculations show that a 50 eV electron produced at an altitude greater than 300 km can escape significant scattering and travel freely upward. Cross-sections for secondary electron production by energetic primary electrons incident upon  $N_2$  have been measured by Opal, et al, (1971). Taking the integrated  $N_2$  density above 300 km for a medium density atmosphere as  $2 \times 10^{15}$  atoms/cm<sup>2</sup> (Johnson, 1965), and the precipitated energy as 3 ergs/cm<sup>2</sup>-sec-str with an average energy of 10 keV we get an expected upward secondary flux at 40 eV from above 300 km of  $.2 \times 10^5$  electrons/cm<sup>2</sup> sec str eV. This is just about equal to the change seen in the 40 eV upward flux in the time period of  $T = 340-440$  seconds as the primary energy flux drops from about 3 ergs/cm<sup>2</sup>-sec-str to .4 ergs/cm<sup>2</sup> sec str. Therefore, although secondary electron production above 300 km appears to contribute

to the upflux of low energy electrons, its contribution is only a minor part of the total observed upflux ( $.2 \times 10^5$  electrons/cm<sup>2</sup> sec str eV out of about  $1.5 \times 10^5$  electrons/cm<sup>2</sup> sec str eV).

As in the case of the secondary electrons, we can also rule out the possibility of magnetic field perturbations as a cause of the large backscatter ratios. First invariant calculations show that an increase of a factor of more than three in the ambient magnetic field is required to cause a particle with a pitch angle of  $30^\circ$  at 585 km to mirror above the neutral atmosphere. Magnetic field changes of this magnitude are not observed in the vicinity of aurorae.

After discounting secondary electrons and magnetic field perturbations, the obvious explanation remaining is the presence of a parallel downward-directed electric field below the rocket of potential drop about 1 keV. A field of this sort would cause the incident auroral electrons with energies less than 1 - 2 keV to mirror above the region of significant scattering in the atmosphere. The backscatter calculations of the previous section have shown that the addition of such a field would give good agreement between calculated and observed backscattered electrons.

There are, however, certain crucial limitations upon this electric field which must be met in this case. The first is that a total potential drop of  $\sim 1$  keV must exist between the rocket altitude and the top of the scattering region (about 150 km for 1 keV electrons). The second is that

no large fraction of this potential drop can exist above 500 km, for there was not a systematic, large variation with altitude of the lowest energy flux in the altitude range 500 - 800 km. Thus for the purpose of discussion we postulate a parallel electric field with a total potential drop of about 1 keV located between 150 and 500 km altitude.

Recent experimental and theoretical investigations have provided a possible source for the postulated electric field. Zmuda et al., (1966), Cloutier et al (1970) and Choy et al (1971) have measured the presence of field-aligned currents composed of very low energy electrons flowing out of the auroral ionosphere. Kindel and Kennel (1971) have theoretically investigated the effects of these currents and have concluded that ion-acoustic and ion-cyclotron instabilities, which are driven by the field-aligned currents, can occur under the conditions found in the auroral ionosphere. The role of the instabilities is to furnish an impedance to the flow of field-aligned currents, and hence to cause a potential drop to develop.

There is, however, a certain difficulty with the application of this mechanism to our particular case. For the range of field-aligned current values expected just from flux balance in the aurora studied here ( $10^8$ - $10^9$  electrons/cm<sup>2</sup>-sec), an examination of Figure 7 of Kindel and Kennel (1971) shows that the first instability expected would be the O<sup>+</sup> or H<sup>+</sup> ion-cyclotron mode, and then only at altitudes greater than 1000 km. We require that the electric field, and hence the instability region, exist below 500 km. A

possible explanation for this apparent inconsistency is as follows. The critical current for instability is not only a function of altitude but also of the electron to ion temperature ratio. As the electrons are heated relative to the ions, ion Landau and cyclotron damping become less important in stabilizing the waves. An examination of Figure 2 of Kindel and Kennel shows that if the ratio of electron drift velocity to electron thermal velocity is initially above a certain value ( $V_d/V_{th} \sim .03$  for  $T_e/T_i = 1$ ), then increasing the  $T_e/T_i$  ratio will cause waves to grow. Therefore, if the electrons in the 150 - 500 km region could be heated sufficiently, then the instabilities and hence the electric fields would exist and be confined to this region. Possible mechanisms for accomplishing this heating include an energy transfer from secondary electrons by means of electrostatic waves (the "bump on tail" instability) or an upward transport of hot electrons from below.

The above argument is necessarily qualitative, for data on crucial parameters such as temperature and drift velocity of the electrons contributing to the field-aligned currents is lacking. It is offered here as a plausible explanation for the required altitude structure of the postulated parallel electric field. Whatever the precise cause, the existence of the parallel downward-directed electric field appears necessary to adequately explain the data shown above.

## CONCLUSIONS

The physical processes which describe the interaction of auroral electrons with the atmosphere appear to be more complex than just the Coulomb scattering of the incident primary electrons with a subsequent loss of energy. The comparison of the measured backscattered electron spectra with spectra predicted using a theoretical scattering calculation has led to a discrepancy for energies below about 1 - 2 keV. It was found that the very high ratio ( $\sim 100\%$ ) of backscattered to incident fluxes for these energies could be most reasonably explained by a parallel downward-directed electric field which prevents these lower energy electrons from entering the atmospheric scattering region. This parallel field with potential drop of about 1 keV is thought to have its origin in wave-particle interactions in the turbulent auroral ionosphere.

#### ACKNOWLEDGEMENTS

The authors are grateful to Dr. L. Westerlund, Mr. J. Sneddon, Mr. F. Abney, and Mr. R. Harrison for their work on the TWINS payload. We are also grateful to Dr. Martin Walt for helpful discussions during the course of the data analysis. This work was funded under contract NASW 2212 from the National Aeronautics and Space Administration.

## REFERENCES

- Bethe, H., Handbuch der Physik, 24, Part 1, Chapter 3, ed. A. Snekal, Springer, Berlin, 1933.
- Chappell, C. R., "The Interaction of Auroral Electrons with the Atmosphere, Ph D Thesis, Rice University, 1968.
- Chase, L. M., "Evidence that the Plasma Sheet is the Source of Auroral Electrons," Jour. Geophys. Res., 74, 348-350, 1969.
- Choy, L. W. and R. L. Arnoldy, "Charged Particle Measurements Over an Auroral Arc," Abstract, Trans. Am. Geophys. Union, 52, 895, 1971.
- Choy, L. W., R. L. Arnoldy, W. Potter, P. Kintner, and L. J. Cahill, Jr., "Field-Aligned Particle Currents Near an Auroral Arc," Jour. Geophys. Res., 76, 8279-8298, 1971.
- Cloutier, P. A., H. R. Anderson, R. J. Park, R. R. Vondrak, R. J. Speiger, and B. R. Sandel, "Detection of Geomagnetically Aligned Currents Associated with an Auroral Arc," Jour. Geophys. Res., 75, 2595-2600, 1970.
- Frank, L. A. and K. L. Ackerson, "Observations of Charged Particle Precipitation into the Auroral Zone," Jour. Geophys. Res., 76, 3612-3643, 1971.
- Johnson, F. S., "Structure of the Upper Atmosphere," in Satellite Environment Handbook, ed. Johnson, Stanford University Press, 1965.
- Kindel, J. M. and C. F. Kennel, "Topside Current Instabilities," Jour. Geophys. Res., 76, 3055-3078, 1971.



- Mott, N. F. and H. S. W. Massey, The Theory of Atomic Collisions, Third Edition, Clarendon Press, Oxford, 1965.
- Moser, F. S. and P. Bruston, "Observation of the Low-Altitude Acceleration of Auroral Protons," Jour. Geophys. Res., 71, 2201-2206, 1966a
- Moser, F. S. and P. Bruston, "Properties of the Auroral-Zone Electron Source Deduced from Electron Spectrums and Angular Distributions," Jour. Geophys. Res., 4451-4467, 1966b
- Moser, F. S. and P. Bruston, "Electric Field Measurements in the Auroral Ionosphere," Jour. Geophys. Res., 72, 1109-1114, 1967
- Nagy, A. F. and P. M. Banks, "Photoelectron Fluxes in the Ionosphere," Jour. Geophys. Res., 75, 6260-6270, 1970.
- Opal, C. B., E. C. Beaty, and W. K. Peterson, "Tables of Energy and Angular Distributions of Electrons Ejected from Simple Gases by Electron Impact," Joint Institute for Laboratory Astrophysics Report No. 108, University of Colorado, 1971.
- O'Brien, B. J., F. Abney, J. Burch, R. LaQuey, R. Harrison, T. Winiecki, SPECS, a Versatile Space-qualified Detector of Charged Particles, Rev. Sci. Instrum. 38, 1058, 1967.
- O'Brien, B. J. and D. L. Reasoner, "Measurements of Highly-Collimated Short-Duration Bursts of Auroral Electrons and Comparison with Existing Auroral Models," Jour. Geophys. Res., 76, 8258-8278, 1971.
- Paulikas, G. A., "The Patterns and Sources of High-Latitude Particle Precipitation," Rev. Geophys., 9, 659-702, 1971.

Rème, H. and J. M. Bosqued, "Evidence Near the Auroral Ionosphere of a Parallel Electric Field Deduced From Energy and Angular Distributions of Low-Energy Particles, Jour. Geophys. Res., 76, 7683-7693, 1971.

Walt, M., W. M. McDonald, and W. E. Francis, "Penetration of Auroral Electrons into the Atmosphere," in Physics of the Magnetosphere, Ed. R. Carovillano and J. F. McClay, p. 534, Reinhold, 1968.

Westerlund, L. H., "The Auroral Energy Spectrum Extended to 45 eV., Jour. Geophys. Res., 74, 351-354, 1969.

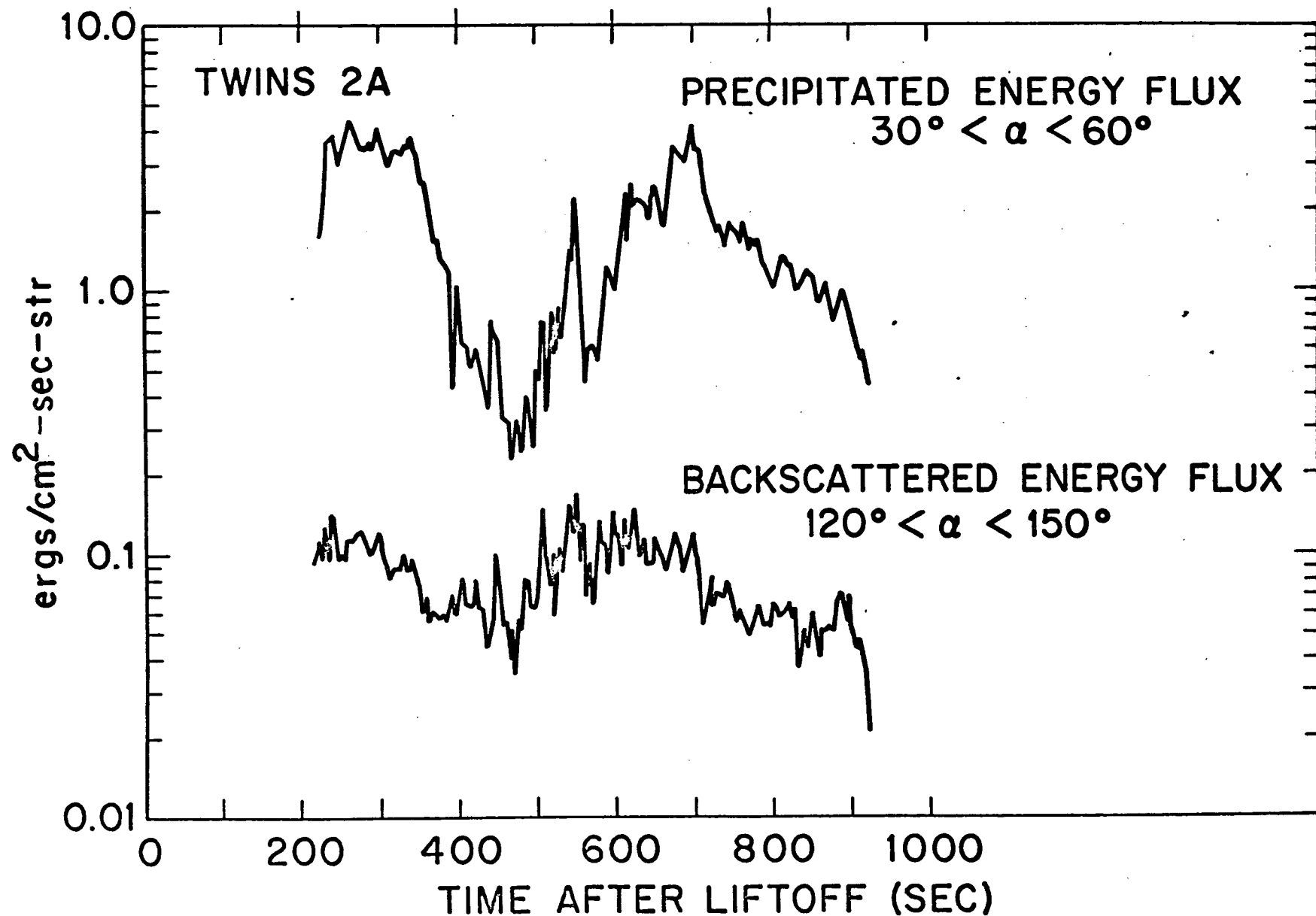
Zmuda, A. J., J. H. Martin and F. T. Huerfing, "Transverse Magnetic Disturbances at 1100 Kilometers in the Auroral Region," Jour. Geophys. Res., 71, 5033-5054, 1966.

## FIGURE CAPTIONS

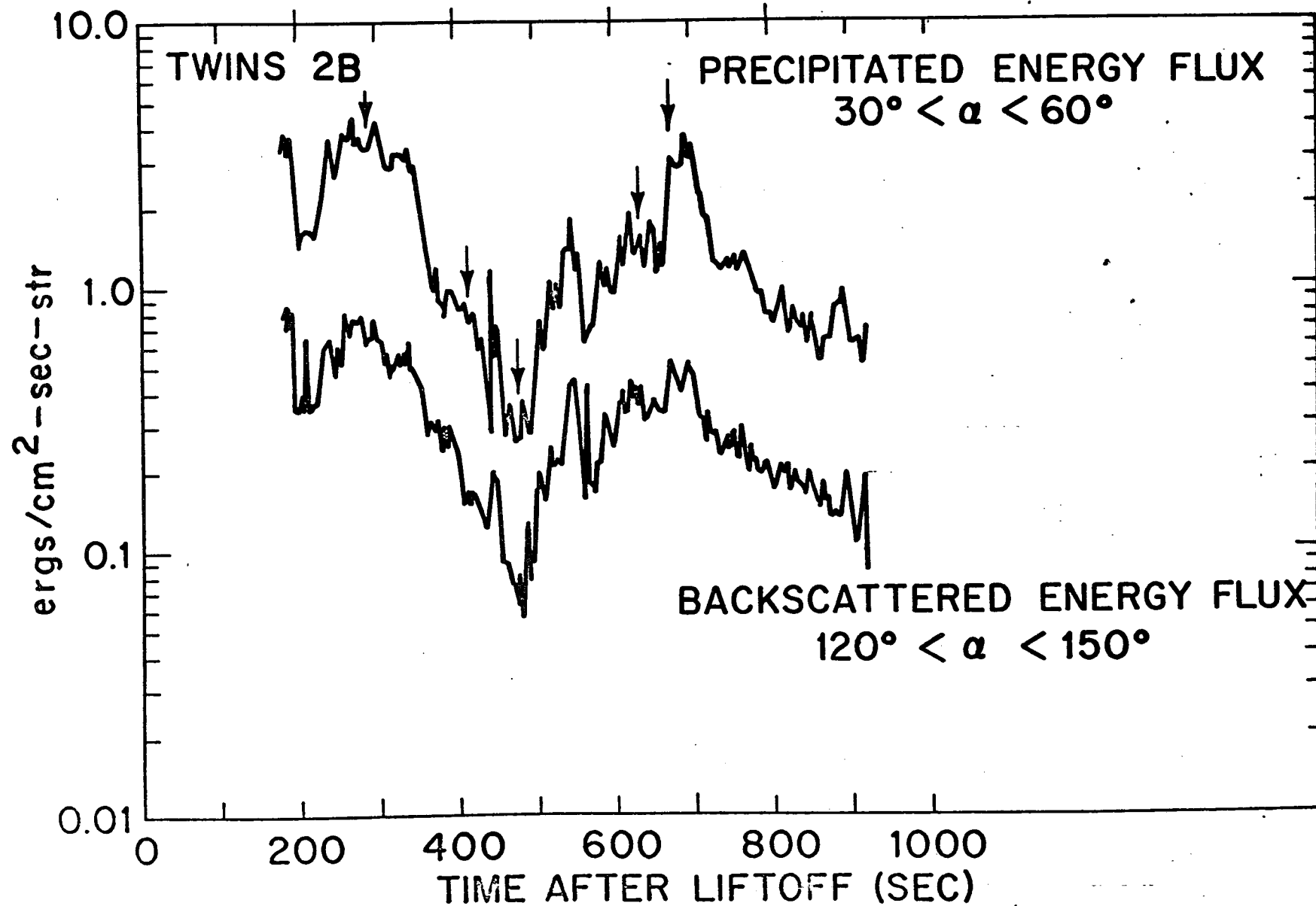
- FIGURE 1      Total directional incident and backscattered electron energy flux measured by TWINS 2A. The measurements were computed by integrating the measured electron spectra, appropriately weighted, over the energy range 400 eV to 20 keV.
- FIGURE 2      Total directional incident and backscattered electron energy flux measured by TWINS 2B. The measurements were computed by integrating the measured electron spectra, appropriately weighted, over the energy range 400 eV to 20 keV.
- FIGURE 3      Incident electron energy spectrum measured at  $T = 281$  seconds. For reference with regard to the time of measurement for this figure and Figures 4 - 9 following, see Figure 2.
- FIGURE 4      Backscattered electron energy spectrum measured at  $T = 281$  seconds.
- FIGURE 5      Incident and backscattered electron energy spectra measured at  $T = 414$  seconds.
- FIGURE 6      Incident and backscattered electron energy spectra measured at  $T = 479$  seconds.
- FIGURE 7      Incident and backscattered electron energy spectra measured at  $T = 630$  seconds.
- FIGURE 8      Incident and backscattered electron energy spectra measured at  $T = 670$  seconds.

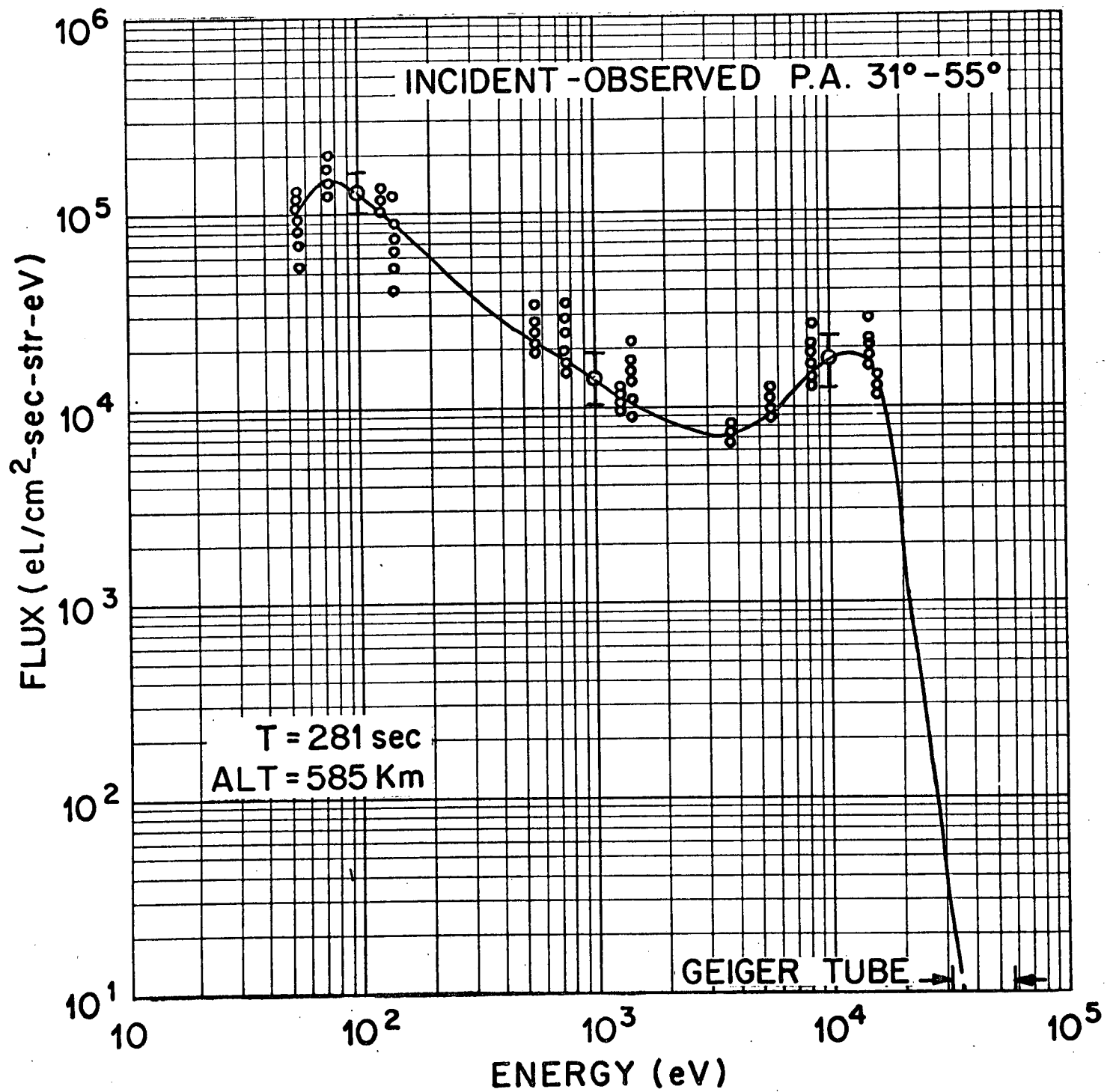
- FIGURE 9      A series of three incident electron energy spectra measured in the period  $T = 351$  to  $T = 405$  seconds showing the shift in the energy of the peak as the payload exits the region over an auroral arc.
- FIGURE 10     Comparison of measured and calculated backscattered electron spectra at  $T = 281$  seconds, a region of intense precipitation.
- FIGURE 11     Comparison of measured and calculated backscattered electron spectra at  $T = 479$  seconds, the time of the minimum precipitation.
- FIGURE 12     Comparison of measured and calculated backscattered electron spectra at  $T = 670$  seconds, a period of intense precipitation.
- FIGURE 13     A comparison of the total incident energy flux (from Figure 1) with the measured 40 eV incident and backscattered flux.

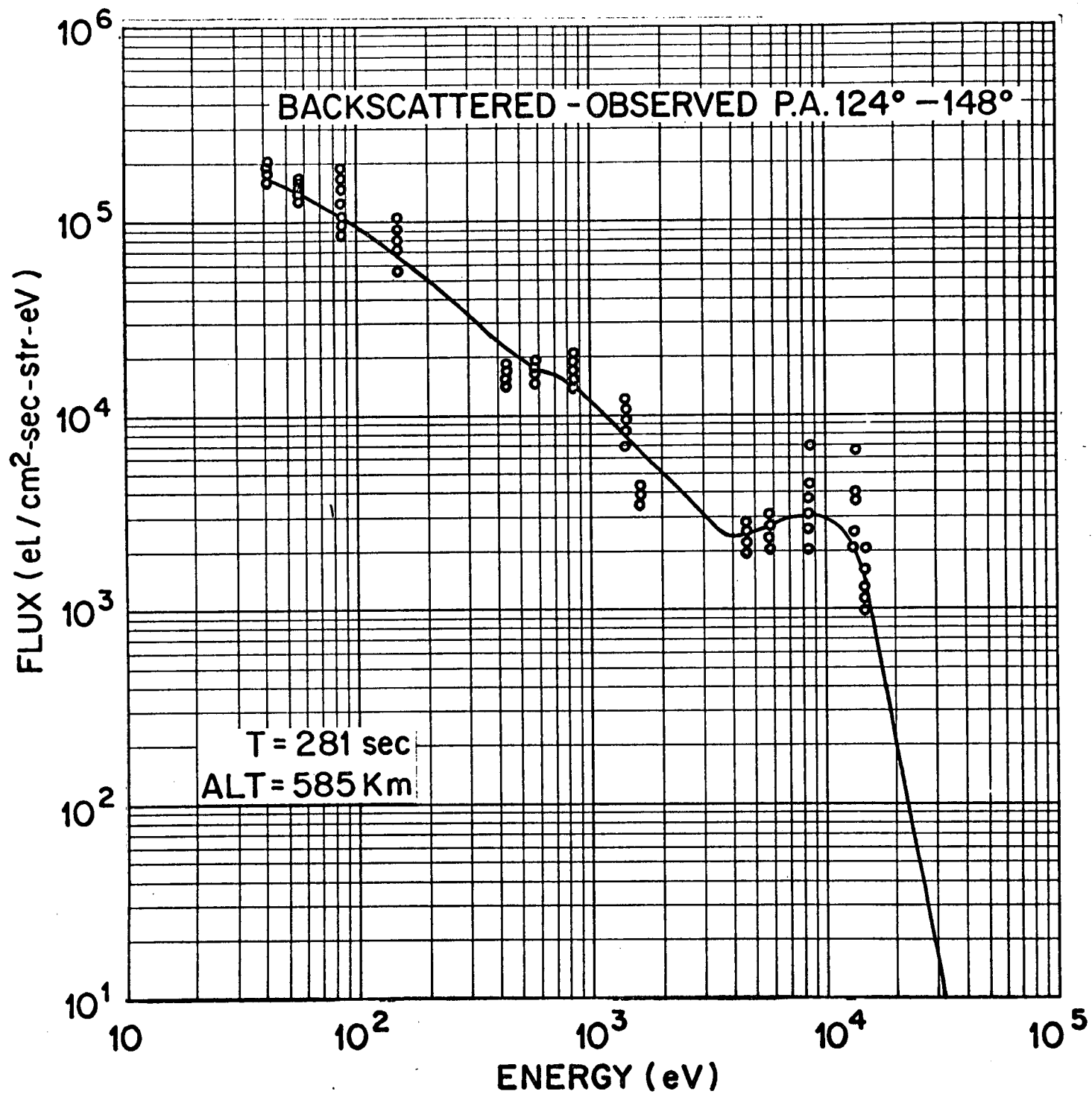
ALTITUDE (KM) 423 744 769 480  
L 9.5 10.7 11.7 12.5



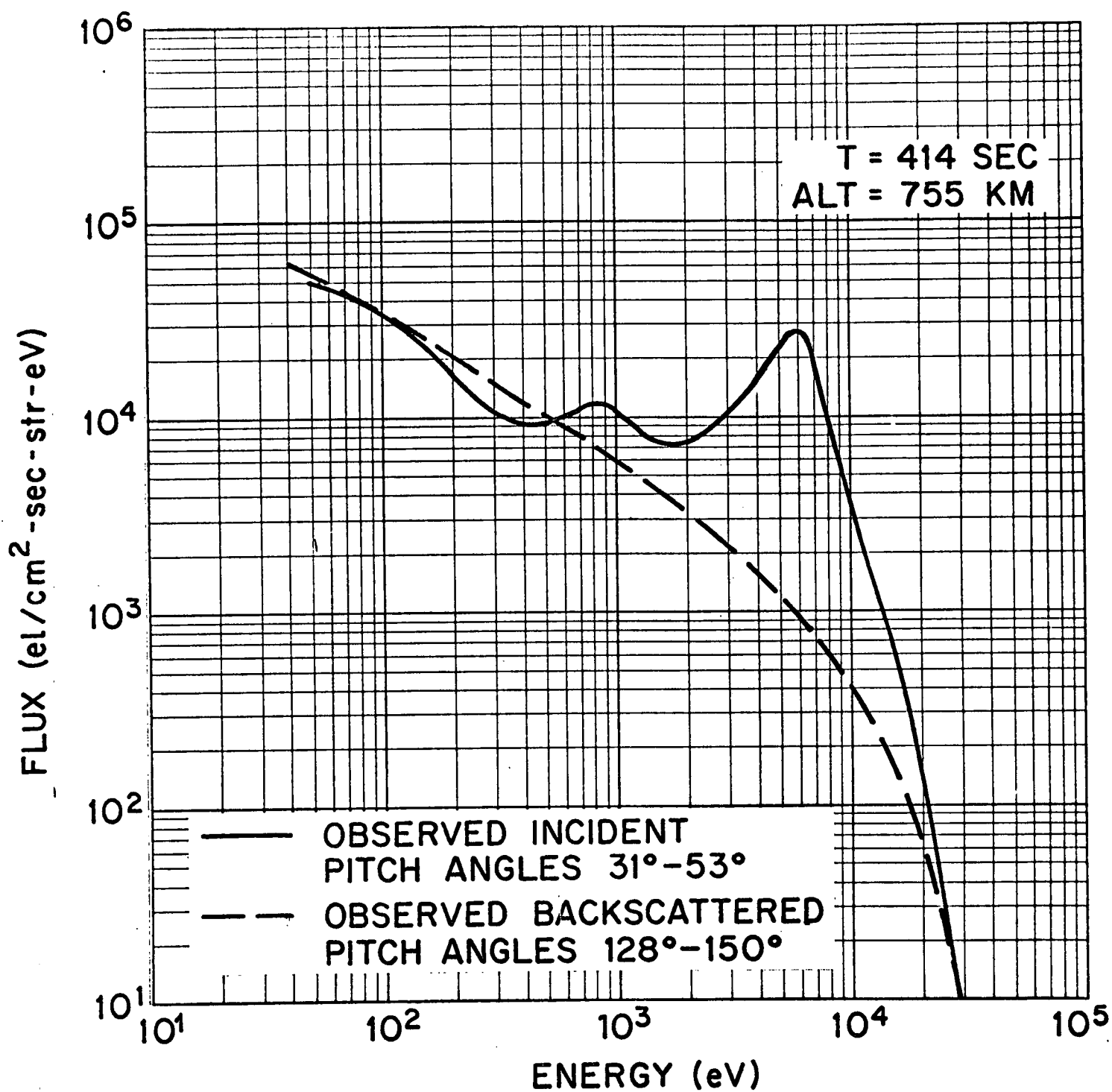
ALTITUDE (KM) 423 744 769 480  
L 9.5 10.7 11.7 12.5

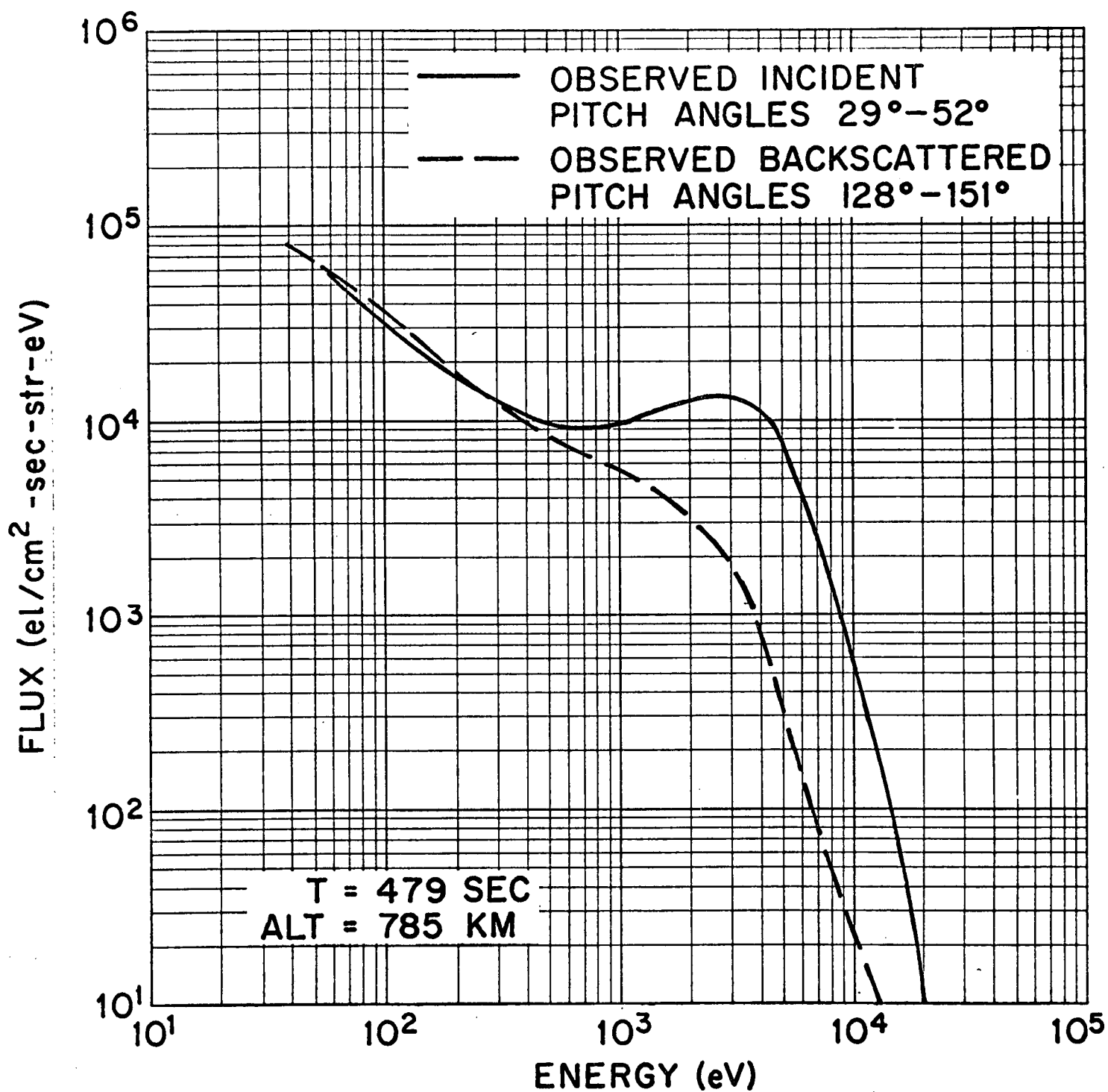


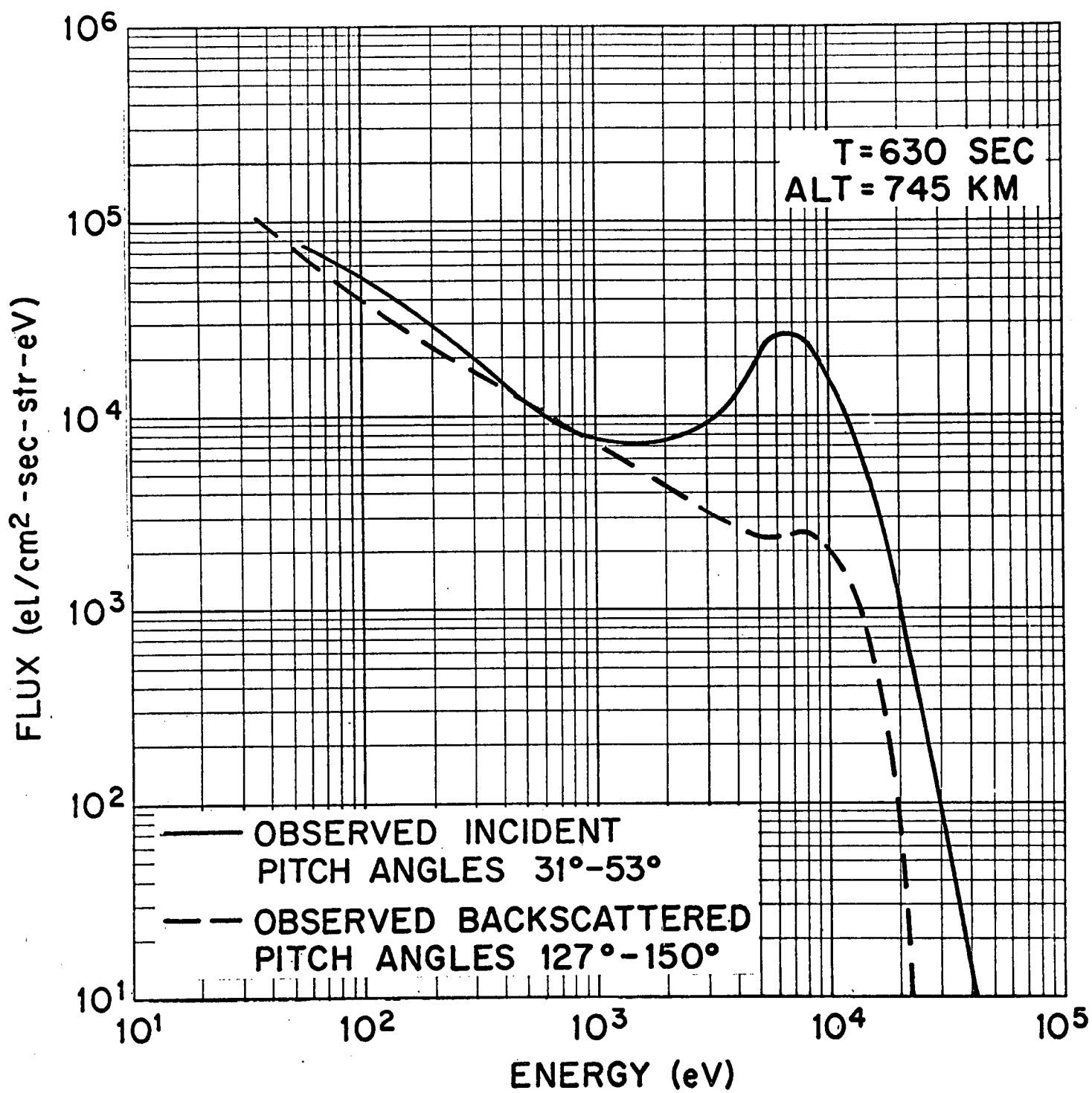


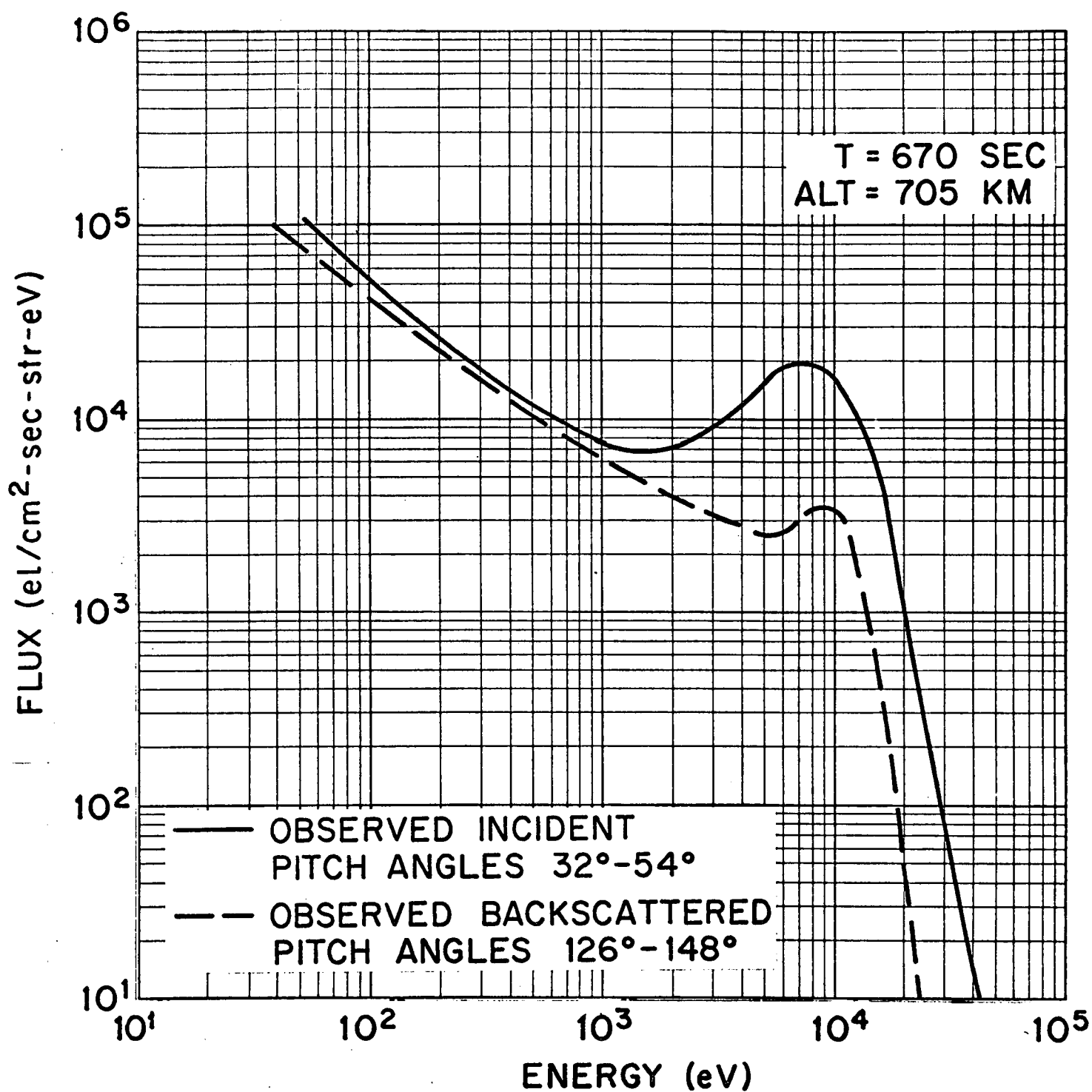


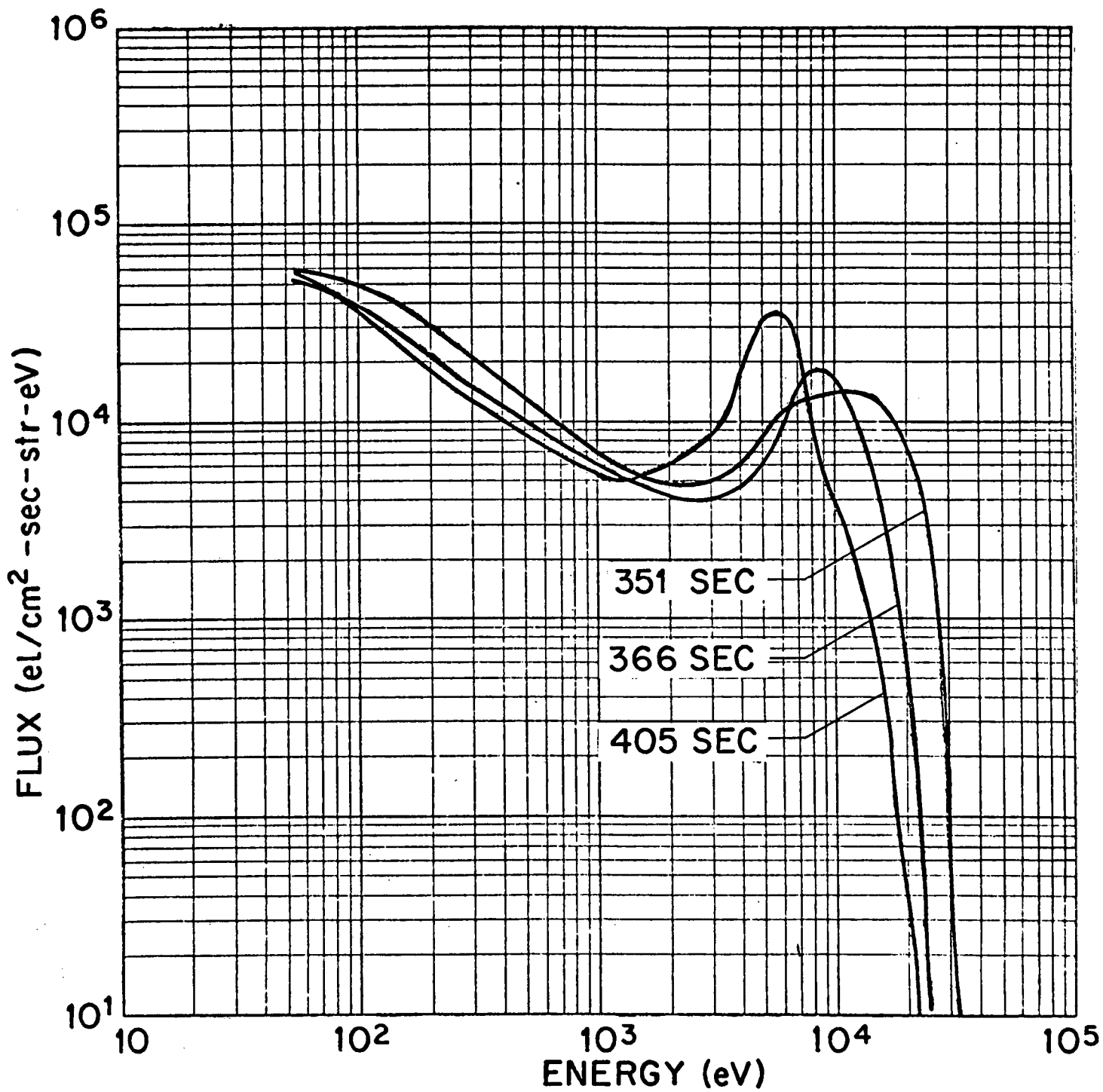










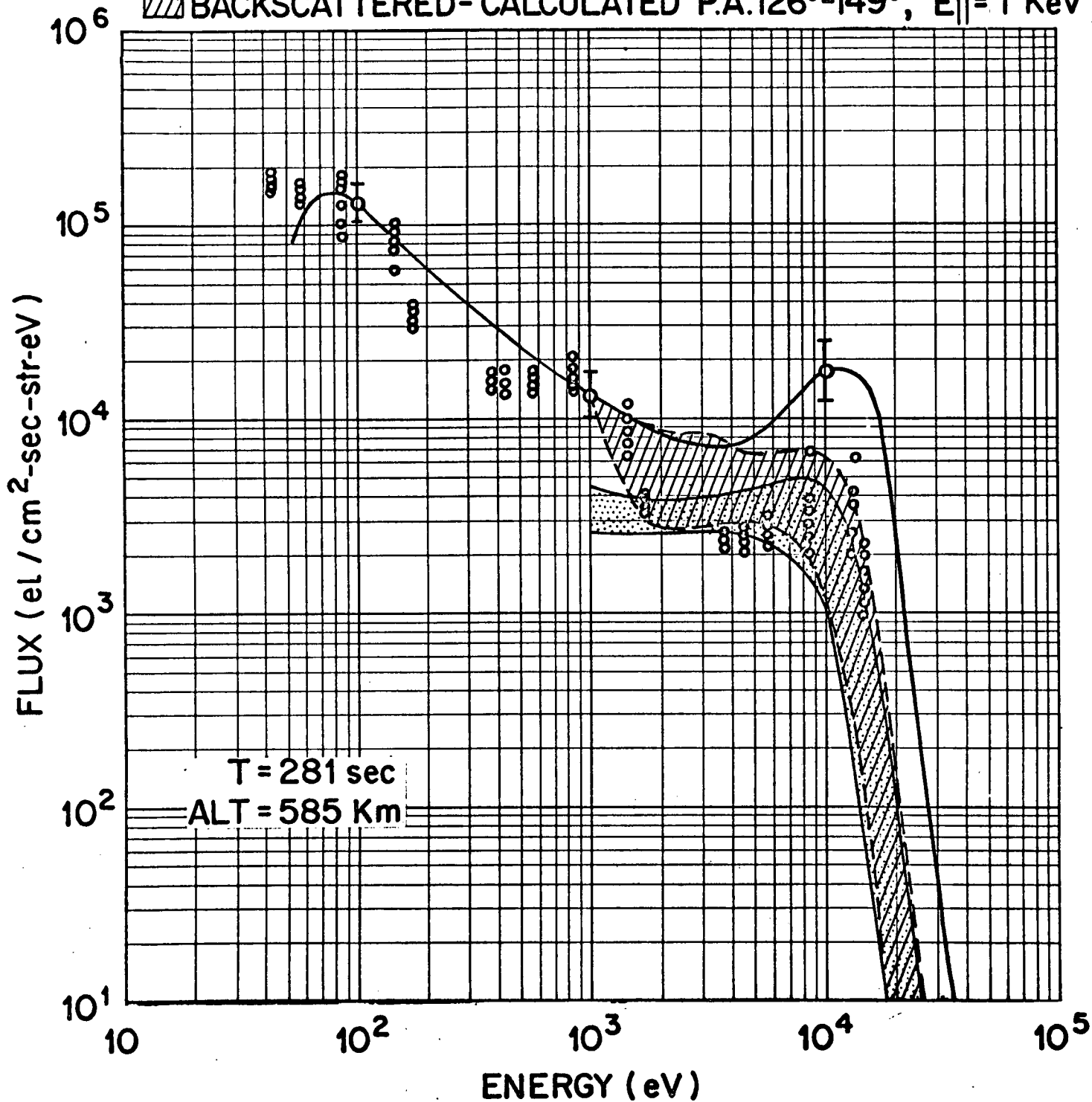


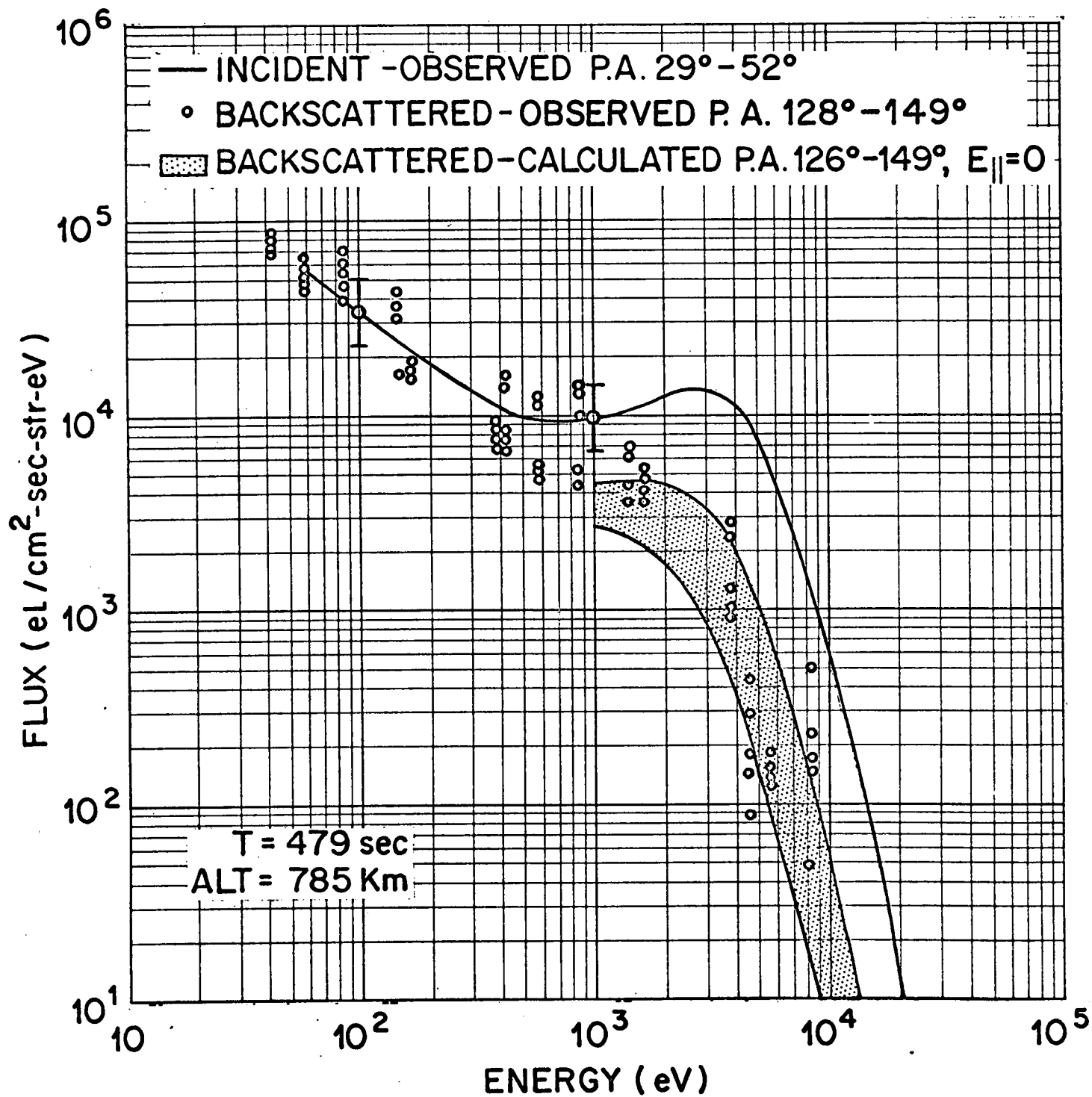
— INCIDENT-OBSERVED P.A.  $32^{\circ}$ - $56^{\circ}$

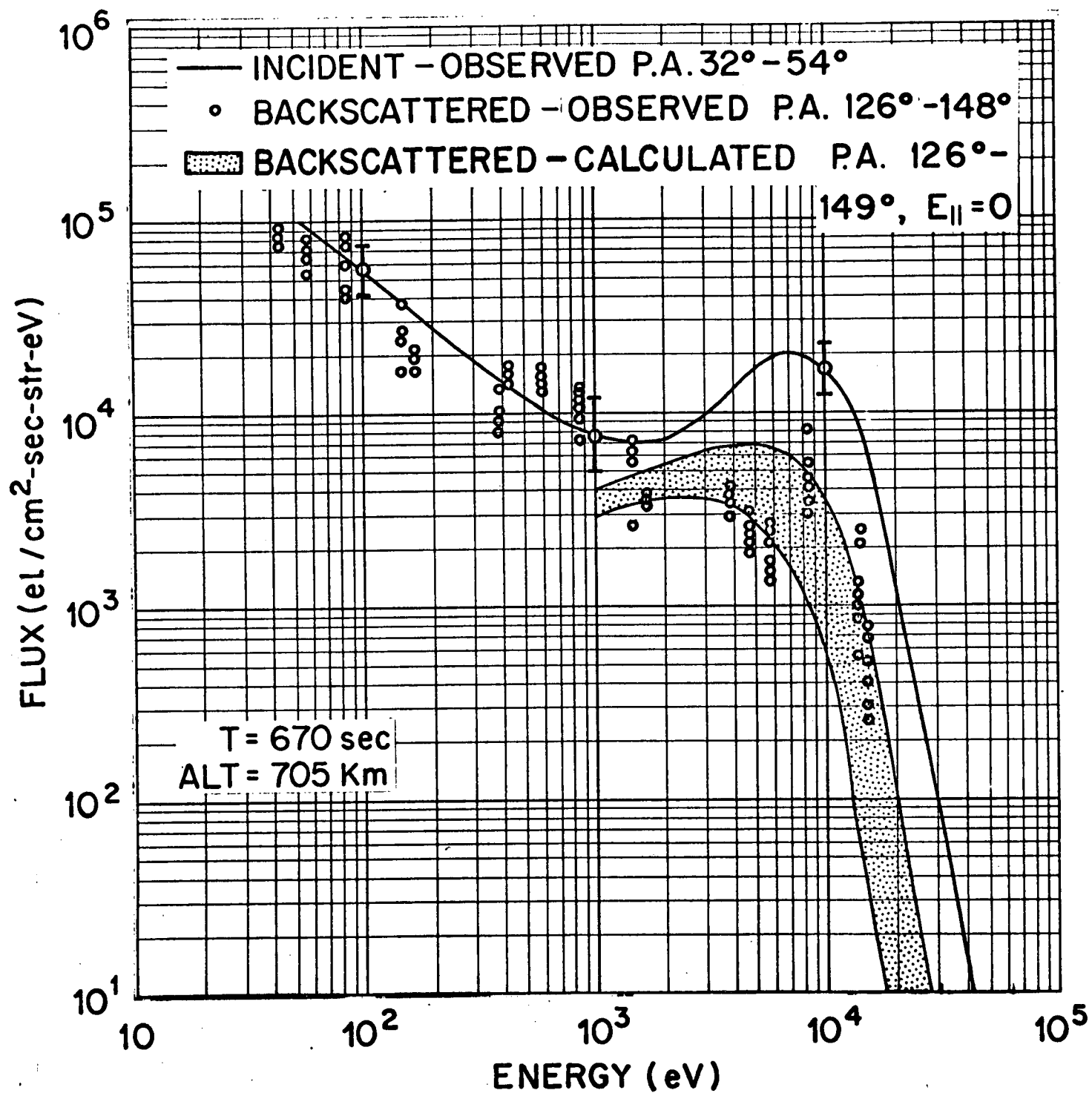
◦ BACKSCATTERED -OBSERVED P.A.  $124^{\circ}$ - $148^{\circ}$

▨ BACKSCATTERED-CALCULATED P.A.  $126^{\circ}$ - $149^{\circ}$ ,  $E_{||}=0$

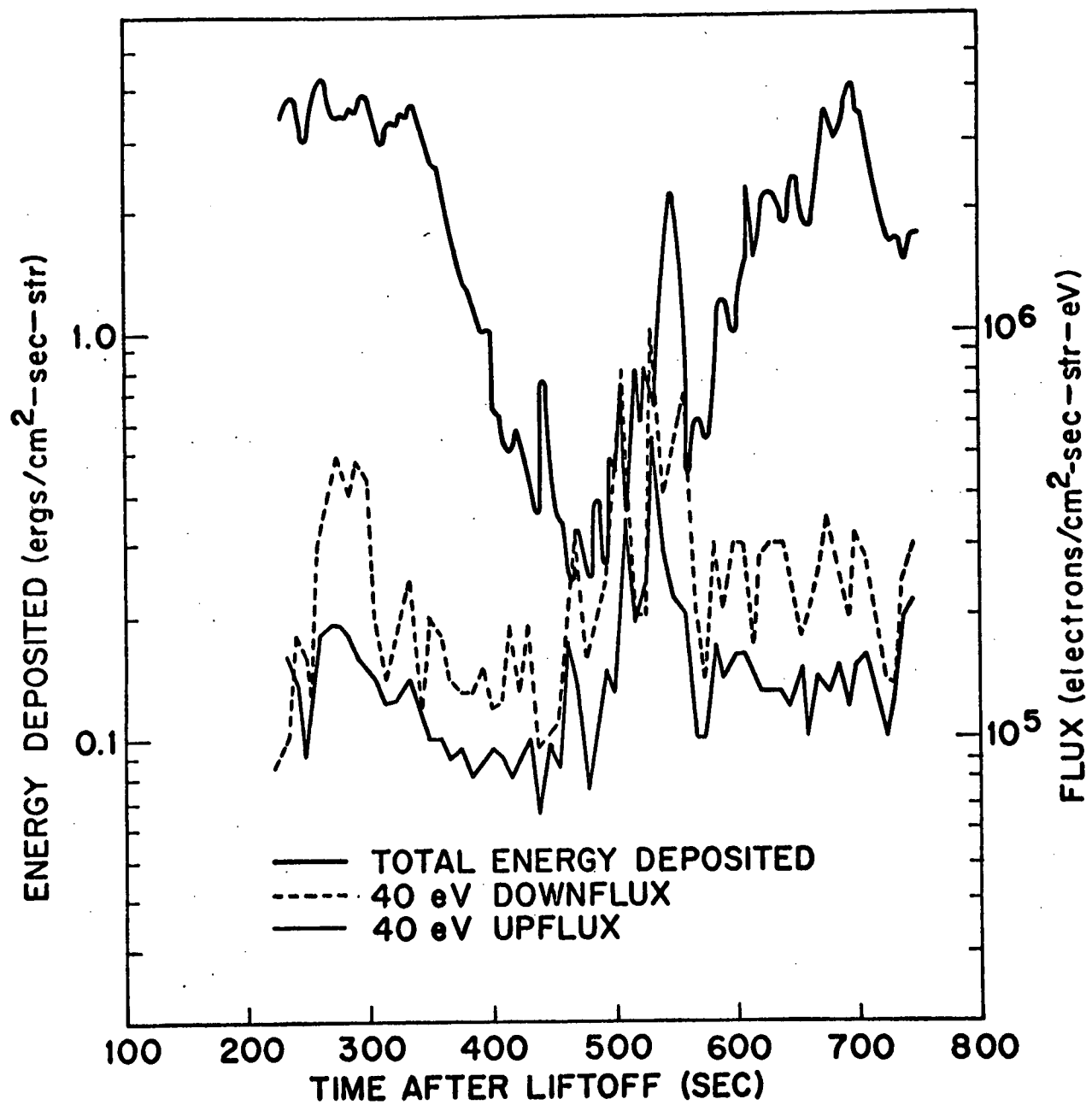
▨ BACKSCATTERED- CALCULATED P.A.  $126^{\circ}$ - $149^{\circ}$ ,  $E_{||}=1$  KeV











## Measurements of Highly Collimated Short-Duration Bursts of Auroral Electrons and Comparison with Existing Auroral Models

BRIAN J. O'BRIEN

*Department of Environmental Protection, Perth, Australia*

DAVID L. REASONER

*Department of Space Science, Rice University, Houston, Texas 77001*

The pitch-angle distributions, energy spectra, and temporal and spatial variations of auroral electrons with energies from 40 eV to 100 keV were measured with the Twins 2 rocket payloads to an altitude of 800 km. Enhancements of electrons with energies of ~5 keV, pitch angle  $\alpha \leq 10^\circ$ , and intensities of up to  $5 \times 10^4$  particles  $\text{cm}^{-2} \text{sec}^{-1} \text{ster}^{-1}$  were observed occasionally. The enhancements were sometimes by a factor of 10, even while electrons with energies of ~12 keV at these pitch angles showed no changes (nor did those with energies between ~40 eV and 100 keV at  $30^\circ \leq \alpha \leq 60^\circ$ ). The bursts were thought to be temporal in origin, and they lasted for the minimum resolvable time of ~0.1 sec up to times of several seconds. The altitude of the source of the bursts of field-aligned electrons is believed to be less than 1  $R_E$ , and their occurrence is not clearly related either to the ever-present auroral continuum nor to the electrons with a few kiloelectron volts that cause auroral luminosity.

We examine several existing theories of auroral particle acceleration and/or precipitation and show them each to be inadequate (as presently formulated) to individually explain all the observations. A potpourri model of adaptations of all these theories is shown to be adequate, but its reality is not otherwise established. Field-line merging and diffusion by wave-particle interactions are considered to be commonly occurring phenomena.

Direct measurements of fluxes of auroral electrons with peak intensity at small pitch angles [Hoffman and Evans, 1968] marked an important experimental breakthrough in auroral physics. Although such a phenomenon had been predicted [see O'Brien, 1967, Figure 6 (12); Speiser, 1965], no experimental evidence supported it for higher-energy electrons (>40 keV) measured at low altitudes [O'Brien, 1964]; indeed, the phenomenon thought had been unlikely if the electrons came from a source high above the atmosphere [Chamberlain, 1961].

Accordingly, with reports of their findings, Hoffman and Evans [1968] formulated a model for the origin of the auroral electrons. To do so, they had to adopt the 'very tenuous assumption' that the variations they observed were of temporal rather than of spatial origin. By contrast, Eather and Akasofu [1969] argue

that the effects were spatial and not temporal and hence that the theory was not proved.

We briefly report here preliminary results of a rocket experiment explicitly planned to distinguish decisively between spatial and temporal effects in auroral-electron fluxes. We find that, up to altitudes of ~800 km and separation distances of up to ~1 km, enhanced fluxes of ~5-keV electrons with small pitch angles were observed simultaneously, on occasion for a time as short as  $\leq 0.1$  sec. We report a summary of the experimental facts and analyze the implications in detail. The effect is believed to be of a temporal origin, rather than of a spatial one. We therefore call the enhancements 'bursts.'

Thus our findings may be regarded as validating the very tenuous assumption of Hoffman and Evans [1968]. However, we argue against their subsequent theoretical conclusions as an explanation for the bursts observed here.

Copyright © 1971 by the American Geophysical Union.

EXPE

The effect was the Twins 2 payload rocket into an orbit over Canada, at 0459. The auroral event consisted of IBC II in the northward, requiring a shift from the southern arc. The arcs were reformed in the region between IBC I glow. It was not the classical arc although there was a ray structure along the magnetometer shadow. The flight azimuth was 120°, and the rocket loads crossed the auroral region approximately 30°.

The top and bottom of the arcs (2B, respectively) were complements to the protons over a wide range of pitch angles. Here the auroral electron fluxes listed in Table 1. The fluxes were stabilized at about 10<sup>4</sup> particles  $\text{cm}^{-2} \text{sec}^{-1} \text{ster}^{-1}$  at an altitude of 800 km, thus achieving a rate of (4 ± 1) m  $\text{sec}^{-1}$  relative and absolute.

Name	
SPECS 1	40
	SON
SPECS 2	40
	SON
High DED	8.7
Low DED 1	3.7
Low DED 2	3.3
8001 Geiger Magnetometer	

\* Orientation refer

# EXPERIMENTAL DETAILS

The effect was found in analysis of data from the Twins 2 payloads, carried by a Javelin rocket into an aurora above Fort Churchill, Canada, at 0459 UT on March 2, 1968. The auroral event consisted of a multiple arc structure of IBC II intensity moving slowly northward, requiring approximately 1 hour to cross from the southern to the northern horizon. The arcs were relatively poorly defined, with the region between the arcs filled with a stable IBC I glow. It should be emphasized that this was not the classic midnight breakup aurora, although there was significant movement of ray structure along the arcs. The Churchill magnetometer showed a small negative bay of 120  $\gamma$ , and the riometer absorption was 1 db. The flight azimuth was 67°, and thus the payloads crossed the visible arcs at an angle of approximately 30°.

The top and bottom Twins packages (2A and 2B, respectively) carried very similar detector complements to measure auroral electrons and protons over a wide range of energies and pitch angles. Here we are concerned only with the auroral electrons measured by detectors listed in Table 1. The two payloads were spin stabilized at about 9 Hz and separated by a spring at an altitude of about 250 km. They thus achieved a relative separation velocity of  $(4 \pm 1) \text{ m sec}^{-1}$  along their trajectory. Their relative and absolute velocity orthogonal to the

geomagnetic field vector  $B$  are the relevant factors here, and their values are  $(1 \pm 0.2) \text{ m sec}^{-1}$  and  $(500 \pm 100) \text{ m sec}^{-1}$ , respectively.

The concept behind this approach was our endeavor to have the two payloads pass, one after the other, through the same region of space, thereby giving a unique opportunity to distinguish spatial from temporal auroral variations, a problem generally acknowledged but often ignored.

The first Twins was launched successfully a year prior to Twins 2, and preliminary analysis of data from one of its payloads was reported [Chappell, 1968; Westerland, 1968, 1969]. Several modifications were made to Twins 2 as a result of study of Twins 1 data, and hence we concentrate on Twins 2.

Analysis of payload orientation and the range of pitch angles studied by the switching proton-electron Channeltron spectrometer (SPECS) instruments [O'Brien *et al.*, 1967] was carried out in much the manner described by Westerland [1968]. On Twins 2 we had the added advantage that the separation-velocity transducer operated. The rocket axis was at an angle of  $(13^\circ \pm 2^\circ)$  to  $B$ , so the upward-viewing SPECS scanned the pitch angle ( $\alpha$ ) from  $\sim 30^\circ$  to  $60^\circ$ , having an opening angle of  $2^\circ$  in  $\alpha$ .

Each differential energy detector (DED) is structurally identical. Particles are collimated by a series of slits and then pass between a pair of electrostatic deflection plates. Particles

TABLE 1. Electron Detectors on a Twin

Name	Energy Range		Orientation*	Sampling Rates	Geometric Factor
SPECS 1	40 ev to 100 kev with six sensors and six voltage steps		$\theta = 45^\circ$	Six sensors stay at one energy range for 0.6 sec, sampling every 10 msec	$10^{-4} \text{ cm}^2 \text{ ster}$
SPECS 2	40 ev to 100 kev with six sensors and six voltage steps		$\theta = 135^\circ$	Six sensors stay at one energy range for 0.6 sec, sampling every 10 msec	$10^{-4} \text{ cm}^2 \text{ ster}$
	Twin 2A	Twin 2B			
High DED	8.6-17 kev	9-17.5 kev	$\theta = 0^\circ$	Every 10 msec	$5 \times 10^{-4} \text{ cm}^2 \text{ ster}$
Low DED 1	3.7-6.7 kev	4.0-7.6 kev	$\theta = 0^\circ$	Every 10 msec	$5 \times 10^{-4} \text{ cm}^2 \text{ ster}$
Low DED 2	3.3-6.3 kev	3.2-5.7 kev	$\theta = 180^\circ$	Every 10 msec	$5 \times 10^{-4} \text{ cm}^2 \text{ ster}$
8001 Geiger	60 kev	60 kev	$\theta = 0^\circ$	Every 10 msec	$5 \times 10^{-4} \text{ cm}^2 \text{ ster}$
Magnetometer			$\theta = 45^\circ$	Every 10 msec	$0.6 \text{ cm}^2 \text{ ster}$

\* Orientation refers to the rocket spin axis.  $\theta = 0^\circ$  is 'up.'

of the proper energy and charge sign (for example, electrons with  $E = 5 \pm 1$  kev) are deflected such that they are incident on the aperture of the Bendix Channeltron [Evans, 1965]. The center energy of the instrument's passband could be adjusted by appropriate selection of the deflection-plate voltage. Each Twins 2 payload carried three such sensors, two oriented parallel to the spin axis ( $\theta = 0^\circ$ ) and the third oriented antiparallel to the spin axis ( $\theta = 180^\circ$ ). (Refer to Table 1 and Appendix 1.)

Nominally, since each DED was mounted parallel to the spin axis, it should have viewed the same pitch angle, namely  $\alpha = 13^\circ$  for the two up-viewing DED's and  $167^\circ$  for the down-viewing DED. In fact, the field of view of the DED is not cylindrically symmetrical (see Figure 1), and indeed it is also not parallel to the instrument mounting bracket and thus not parallel to the rocket axis. The center of the field of view is only  $3^\circ$  from the rocket axis, and prior to launch we judged this to be trivial and quite tolerable. In fact, the precision of this serendipity is what led to the discovery reported here.

Counts from all sensors were fed to individual 12-bit accumulators, with the exception that channels 3 and 4 of each SPECS were commutated. Magnetometer outputs were digitized and transmitted as a 6-bit word. Each pulse-code modulation system had a frame length of 216 bits, and a bit rate of about 20,000 bits per sec, and thus the sampling rate of each sensor was about 100 times per sec. The deflection voltage changed on each SPECS each 0.6 sec, giving a complete spectrum every 3.6 sec and the background (plate voltage zero) every 40 sec.

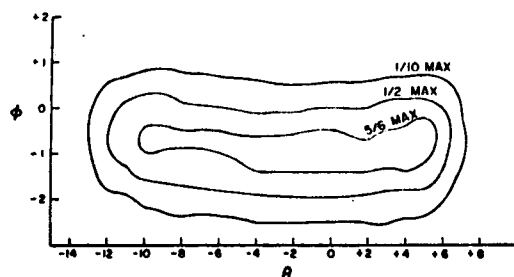


Fig. 1. Angular response of the DED sensor.

#### EXPERIMENTAL RESULTS

On various occasions during the flight, the output of the low DED's (5 kev) on each payload showed a marked modulation at twice the spin period of nominal 9 Hz. The modulation, seen simultaneously with both payloads, would sometimes be in phase (Figure 2) and sometimes not in phase (Figure 3). Owing to various dynamical effects at separation, the final spin rates of the two Twins payloads differed by approximately 0.02 Hz. In all instances, however, the modulation seen on each Twin was quite clearly in phase with the maximums and minimums of the  $45^\circ$  magnetometer on that Twin. This magnetometer lies in the plane of the  $\theta$  or long axis of the DED field of view (Figure 1), and hence, when the magnetometer is at a maximum or minimum, the plane defined by the long angular DED acceptance opening, the  $\theta$  plane, very closely contains the geomagnetic  $B$  vector. At these times, the detector instantaneously samples pitch angles ranging from  $\sim 1^\circ$  to  $\sim 19^\circ$  or from  $\sim 7^\circ$  to  $\sim 25^\circ$ . The combination of the above quoted conditions, namely the presence of the modulation, the phasing of the modulation with respect to the magnetometers, the in-phase and out-of-phase nature of the modulations matching with the in-phase and out-of-phase nature of the payload spins, and finally the characteristics and orientation of the DED angular response function all lead to the conclusion that, on the occasion during a spin when the DED count was enhanced, it was receiving electrons from a smaller or larger pitch angle than  $13^\circ$  where the intensity was greater. The modulation of the DED data at exactly twice the spin rate is therefore due to the fan-shaped angular response of the DED sampling a strongly anisotropic pitch-angle distribution, and the envelopes of the peaks of the modulation show the temporal history of these anisotropy events.

Because the most common pitch-angle distributions of magnetospheric electrons are peaked at  $\alpha \sim 90^\circ$  [see O'Brien, 1964], one might at first think, therefore, that the occasional enhancements of the DED sensors were due to its acceptance of electrons with pitch angles larger than  $\alpha \sim 13^\circ$ , say at  $\alpha \sim 25^\circ$  (see Figure 1). In fact, we now show it to be due instead to the acceptance of electrons with pitch angles smaller than  $\alpha \sim 13^\circ$  and, indeed,

with  $\alpha \lesssim 10^\circ$ . We show this by demonstrating that comparable energy at SPECS are too small to give the observed enhancement rates.

From preflight calibration with a  $\text{Ni}^{55}$  source, it may be seen that a deflection voltage of 100 V (see here) that the sum of SPECS was about 36

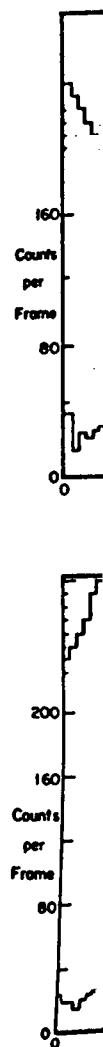


Fig. 2. Short-lived modulation in two payloads due to the fan-shaped response of the DED.

with  $\alpha \lesssim 10^\circ$ . We show this causation simply by demonstrating that the fluxes of electrons of comparable energy at  $\alpha \sim 30^\circ$  as viewed by SPECS are too small by factors of about 10 to give the observed enhancements of the DED rates.

From preflight calibrations with a 3.3 mc  $\text{Ni}^{60}$  source, it may be noted that we found (at a deflection voltage of  $-3500$  volts, relevant here) that the sum of channels 1 and 2 in SPECS was about 36 per sec, whereas that of

the low DED's was about 35 per sec. Thus the relation (ch.1 + ch.2) counts = low DED counts seems applicable here.

We also examined flight data to show that this relation continued to exist. We chose not only isotropic fluxes (Figure 4), but, instead, we plotted a random set of 1-sec sums of low DED against 49-frame (0.5 sec) sums of (ch.1 + ch.2) counts at  $-3500$  volts at the same times (Figure 5). It can be seen from Figure 5 that for many of the plotted points (say about

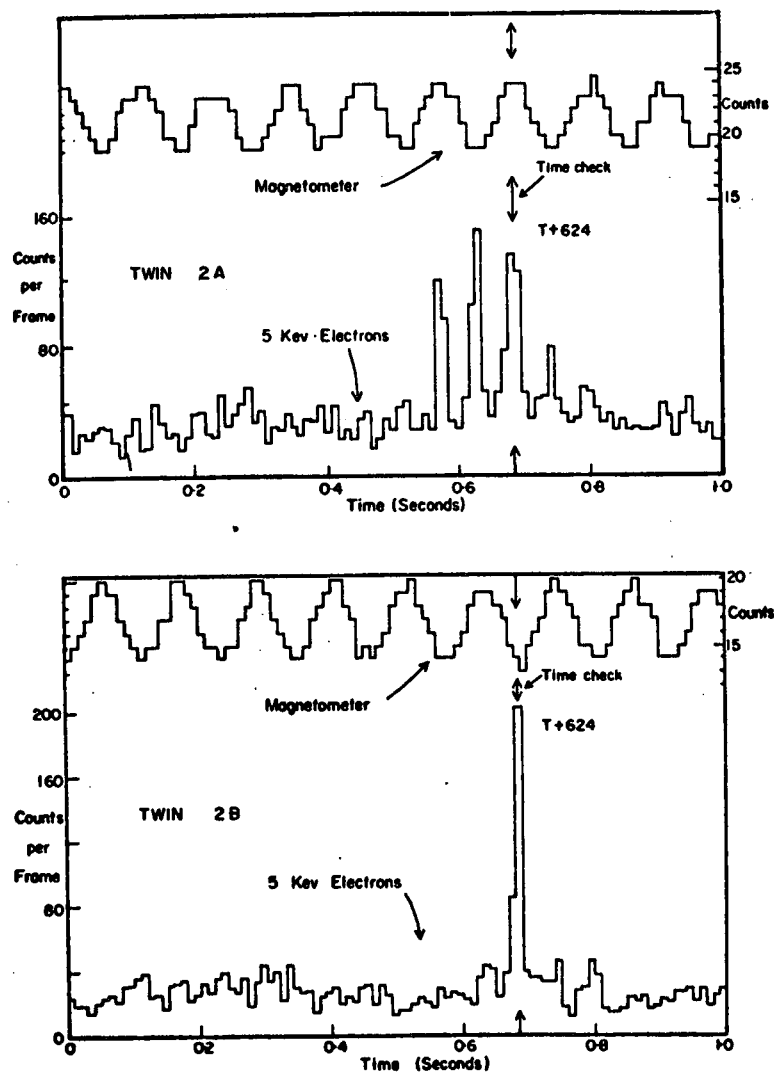


Fig. 2. Short-lived enhancement of the flux of 5-keV electrons observed simultaneously in two payloads about 1 km laterally apart. The modulation at twice the spin rate is due to the fan-shaped response of Figure 1 coupled with a strongly anisotropic flux. (See text.)

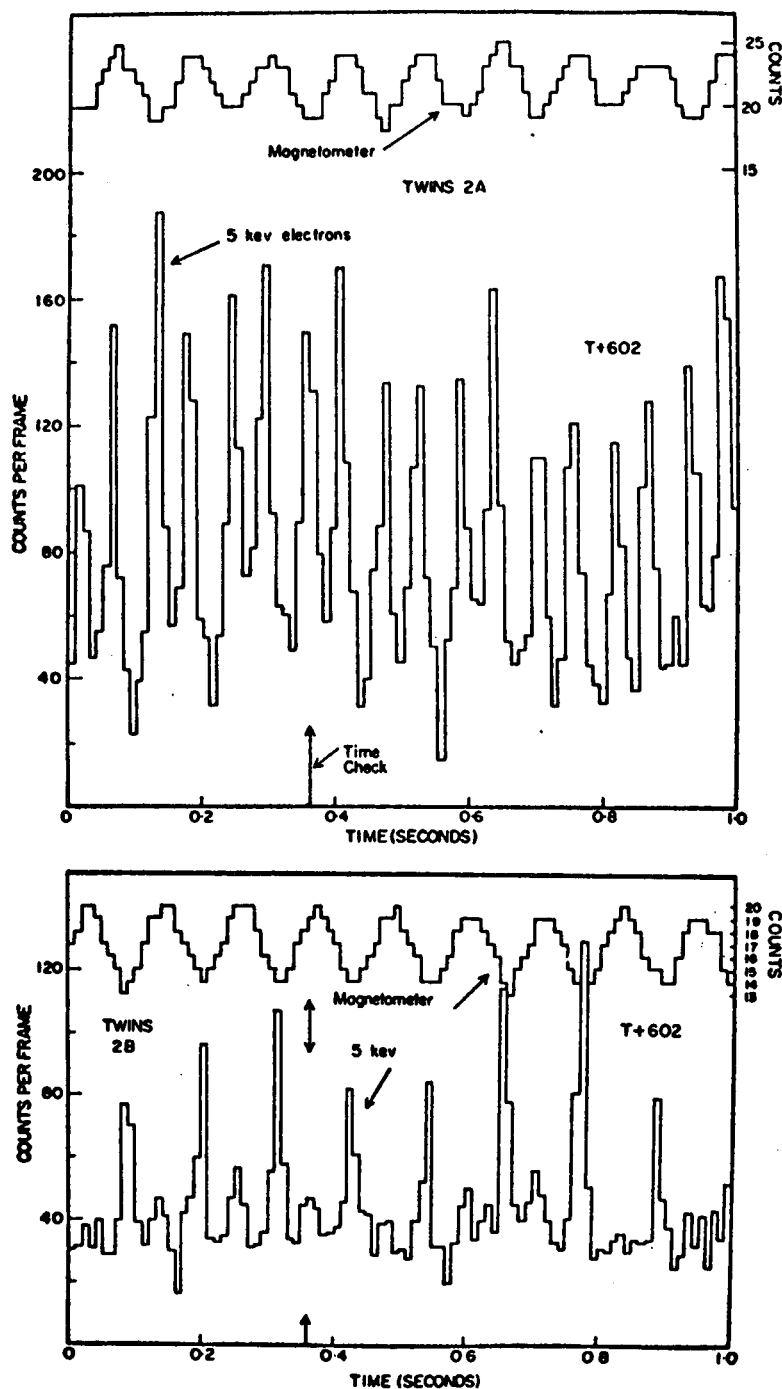


Fig. 3. Similar to Figure 2 but for a time when the magnetometers of the two payloads are out of phase. The modulation is shown to be due to the cause mentioned in the legend of Figure 2 rather than to a periodic modulation of an electron flux.

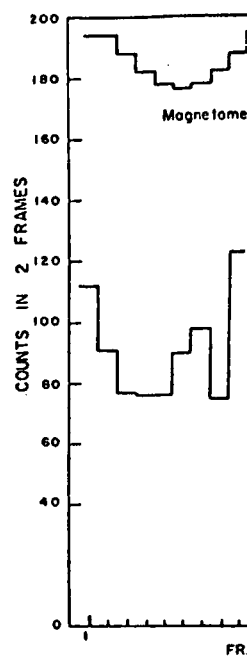


Fig. 4. Essentially five relative geometries after launch. The low DED after launch magnetometer output and 2 at -3500 volts. Two complete spins in frame 1 have been added and to those that follow for accuracy.

half) the preflight modulation remained the greatest slope line in the sense of counts, and we find strong modulation effects. Several scatter to this effect pitch-angle and spectral whole number of points in the range  $R \approx (1.0 \pm$

$$R = \frac{\text{sum of channels}}{\text{low}}$$

This value of  $R$  is, to both Twins 2A and spectra where the ratio to that of channel 2 is between  $\sim 1:8$  and  $\sim 1:4$  over only a 2-kev range. The general of the modulation

Consider the event

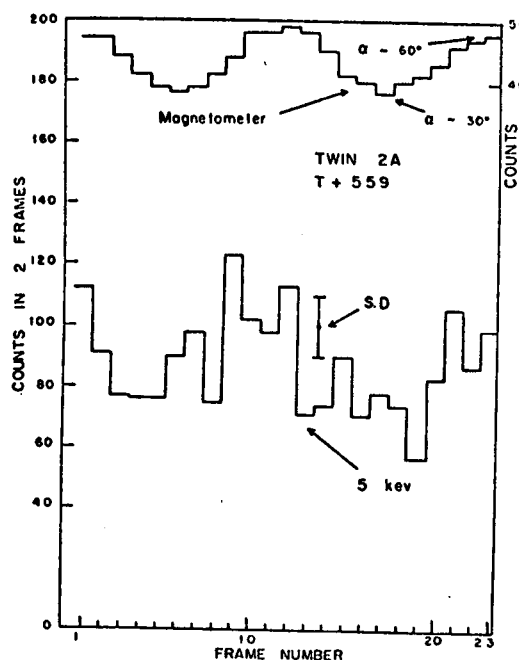


Fig. 4. Essentially isotropic flux used to derive relative geometric factors for SPECS and low DED after launch. The graph shows the magnetometer output and the sum of channels 1 and 2 at  $-3500$  volts deflection. Since there are two complete spins in  $\sim 23$  frames, counts in frame 1 have been added to those in frame 24 and to those that follow to improve statistical accuracy.

half) the preflight relation is valid. We examined the greatest deviations from the unit slope line in the sense of anomalously high DED counts, and we find some, but not all, having strong modulation effects. We attribute the general scatter to this effect and to differences in pitch-angle and spectral distributions. Of the whole number of points, about two-thirds are in the range  $R \approx (1.0 \pm 0.3)$ , where

$$R = \frac{\text{sum of channels 1 and 2 rates}}{\text{low DED rates}}$$

This value of  $R$  is, for this study, applicable to both Twins 2A and 2B over a wide range of spectra where the ratio of the rate of channel 1 to that of channel 2 varies, for example, between  $\sim 1:8$  and  $\sim 4:1$ , i.e., a 30-fold change over only a 2-keV range. We now examine several of the modulation events in detail.

Consider the event at  $T + 624$  sec (Figures

2 and 6 and Table 2). From the combined counts of 1557 counts in channels 1 and 2 in 49 frames, one would predict a low DED rate of 32 counts per frame, or using the above range in  $R$ , a count of  $(32 \pm 10)$ . In fact (Figure 2), the peak rate was 150, and the minimum was around 30. Thus one can indeed use the SPECS data to predict low DED rates when it is viewing larger pitch angles, but the flux at lower pitch angles is abnormally high. The above example for Twins 2A is given by 2B also. From SPECS sampled at the  $-3500$  volts level 1 sec later, one would predict a rate of  $(12.7 \pm 3)$  for the low DED, whereas in fact the maximum was 202, and the minimum was around 30.

Consider again the event at  $T + 616$  sec (Figure 8). From the SPECS, one would predict a DED rate of  $(27 \pm 5)$ , whereas in fact we found maximums of 242 and minimums around 20.

In every instance of significant spin-induced modulation we examined, we find the same conclusion, namely that electron fluxes at  $\alpha \sim 30^\circ$  are inadequate by factors of about 10 to explain the low DED count rates.

Of course the off-axis and fan-shaped angular response of the DED (Figure 1), which accounts for the modulation at twice the spin rate, means

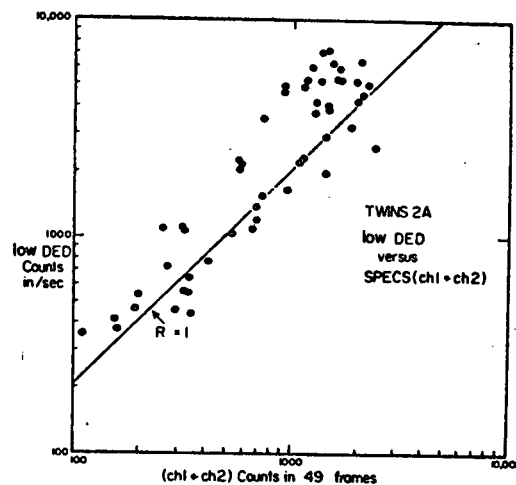


Fig. 5. Scatter plot of randomly chosen comparison of low DED versus channel 1 plus channel 2 rates. The line  $R = 1$  represents equal counting rates to compare in-flight geometric factors, as in Figure 4.

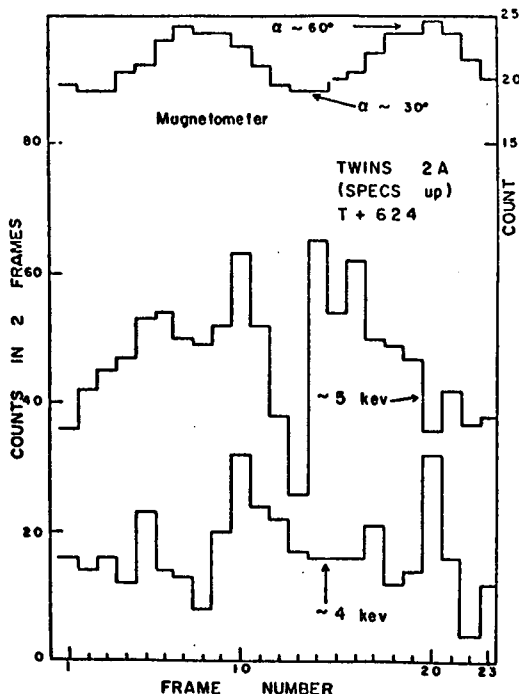


Fig. 6. Pitch-angle distribution (from Figure 4) at the time of the enhancement of Figure 2. Note the erratic form of the data.

that at one instant the detector is sampling pitch angles of  $1^\circ$  to  $19^\circ$ , and half a revolution later the detector is sampling pitch angles of  $7^\circ$  to  $25^\circ$ . At the minimums in the modulations, the pitch angles being sampled are from  $\sim 12^\circ$  to  $15^\circ$  (see Figure 1). Hence we can make the important conclusion that the DED enhancement is due to electrons with  $\alpha \lesssim 10^\circ$ . This conclusion is not only important in itself, but, since only portions of the DED field of view detects these electrons, the enhancements represent fluxes even more intense than the ratio of count rates would imply.

Therefore we find that the flux of precipitated electrons at an altitude of  $\sim 750$  km is enhanced by a factor of  $\sim 10$  at pitch angles  $\alpha \lesssim 10^\circ$ , whereas electrons of comparable energy ( $\sim 4$  to  $7$  keV) at pitch angles of  $\sim 30^\circ$  to  $60^\circ$  are not appreciably affected.

#### EFFECTS AT OTHER ELECTRON ENERGIES

We now briefly examine the behavior of other electrons at the times of such a dramatic surge. We have yet to detect any significant effect,

although further studies are being pursued. To illustrate the problem, the outputs of all sensors on Twins 2 for a few frames before and after the large pulse of Figure 2 are listed in Tables 2 and 3.

Generally we do find that, during such enhancements, the pitch-angle distribution is erratic (Figure 6) or more clearly peaked at  $\alpha \sim 60^\circ$  rather than at  $\alpha \sim 30^\circ$  (Figure 7). We thus have a distribution with one peak at  $\alpha > 60^\circ$  and another intense peak at  $\alpha > 10^\circ$ , the two distributions apparently behaving independently, as is evident from Table 2 and the following related discussion. (Note that, since the existence of the modulation is dependent on the existence of pitch-angle anisotropies, we do not find any clear-cut examples of modulations in the DED data when the SPECS indicates relative isotropy over  $30^\circ < \alpha < 60^\circ$ . However, we are not yet able to test the important question of whether enhance-

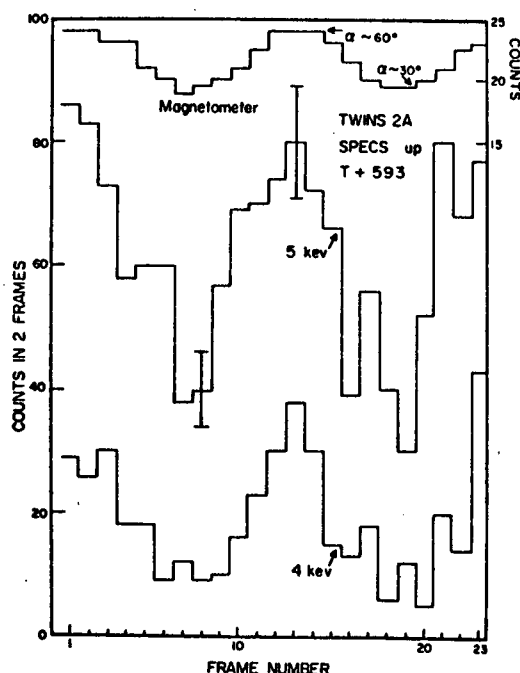


Fig. 7. Similar to Figure 6 but showing a clearer anisotropy over  $30^\circ < \alpha < 60^\circ$ . Enhancements of up to 120 counts were observed in the low DED's at the time with minimums of  $\sim 20$  counts per frame. This example also validates the analysis that the electrons with  $\alpha \lesssim 10^\circ$  are enhanced.

TABLE

Frame Number	Magnetometer
1011	21
1012	23
1013	24
1014	24
1015	24
1016	22
1017	21
1018	20
1019	19
1020	19
1021	20
1022	21

\* Note that the 2B s

ments at  $\alpha < 10^\circ$  isotropic fluxes.)

As we examine T several facts. First, effect in the high I went up to 202 coun view of both detecto in this instance the a have been confined However, in other p was such an enhan Twins 2B, but, owing lar device on 2A a prove these effects t not treated here.

We would not exp to detect an enhan electrons for severa the enhanced prec

TABLE

Frame Number	Magnetometer
120	18
121	17
122	15
123	14
124	13
125	15
126	16
127	17
128	19
129	20
130	19
131	18



TABLE 2. Twins 2A Sample Responses around a 'BURST' at  $T + 624$ 

Frame Number	Magnetometer	Low DED 1		High DED		SPECS 1				
		5 kev down 2A	2B*	12 kev down (on 2B)	8001 GM 60 kev down	4 kev	5 kev	7 kev	12 kev	25 kev
1011	21	50	24	6	1	15	28		2	0
1012	23	76	39	11	0	6	36			0
1013	24	135	86	8	4	4	23	76		0
1014	24	125	202	9	3	2	29		0	0
1015	24	51	40	14	4	10	26			0
1016	22	34	37	8	0	18	37	78		0
1017	21	46	36	11	1	18	40		4	0
1018	20	47	33	10	1	16	14			0
1019	19	78	33	7	3	4	18	83		0
1020	19	46	47	13	2	10	29		0	0
1021	20	37	18	12	1	10	35			0
1022	21	32	12	11	5	10	31	90		0

\* Note that the 2B sensors were sampled 4 msec (about half a frame) before those of 2A. See Figure 2.

ments at  $\alpha < 10^\circ$  never arise over otherwise isotropic fluxes.)

As we examine Tables 2 and 3, we note several facts. First, there is no perceptible effect in the high DED when the low DED went up to 202 counts per frame. The fields of view of both detectors are identical, and thus in this instance the  $\alpha < 10^\circ$  enhancement must have been confined to energies  $E < 7$  kev. However, in other portions of the flight there was such an enhancement in high DED on Twins 2B, but, owing to the failure of the similar device on 2A after separation, we cannot prove these effects to be temporal, and they are not treated here.

We would not expect the down-viewing DED to detect an enhanced flux of backscattered electrons for several reasons. The solid angle of the enhanced precipitation is small, and the

backscattered flux would be dispersed in pitch angle and degraded in energy, with resultant dispersal of arrival times back at the payload. Thus we see no increase in the down-viewing DED count rates. (See Table 3.)

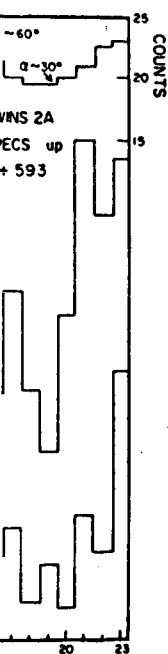
As one views Table 3, it might be thought significant that there was apparently an increased upflux seen in channels 1, 2, and 5 of the down-viewing SPECS in the frame after the 'pulse.' Indeed, each count rate was more than twice its 49-frame average of 3.7, 3.3, and 5.8, respectively. The number of times the counts of 11, 7, and 16, respectively, were equaled or exceeded in the other 48 frames were 0, 6, and 1 times, respectively. Thus the probability of all three occurring by chance in this one frame after the pulse is of the order of 1 part in 10 thousand. Actually, it is even less than that, because the other high count rates

TABLE 3. Twins 2B Sample Responses around a 'BURST' at  $T + 624$ 

Frame Number	Magnetometer	Low DED		SPECS 2, upmoving				
		5 kev down	5 kev up	40 ev	60 ev	80 ev	140 ev	350 ev
120	18	24	4	3	4		6	5
121	17	39	2	9	2			6
122	15	86	1	4	2	1		3
123	14	202	1	4	0		4	16
124	13	40	3	11	7			10
125	15	37	5	5	7	4		2
126	16	36	1	3	2		0	6
127	17	33	1	3	4			7
128	19	33	3	7	6	3		12
129	20	47	3	3	9		1	7
130	19	18	2	4	2			3
131	18	12	1	4	2	2		

ing pursued. To  
ts of all sensors  
before and after  
listed in Tables

during such en-  
distribution is  
early peaked at  
30° (Figure 7).  
with one peak at  
peak at  $\alpha > 10^\circ$ ,  
ly behaving in-  
m Table 2 and  
on. (Note that,  
modulation is de-  
ch-angle aniso-  
ar-cut examples  
data when the  
ny over 30° <  
yet able to test  
whether enhance-



but showing a  
 $\alpha < 60^\circ$ . En-  
were observed in  
h minimums of  
le also validates  
with  $\alpha \leq 10^\circ$  are

occurred, as one would expect, at smaller pitch angles ( $\alpha \sim 120^\circ$ ), whereas the quoted numbers were for the maximum pitch angle sampled, namely  $\alpha = 150^\circ$ .

Therefore, from these data alone, one cannot rule out the chance that there was an enhancement of up-moving 100-ev electrons close to *B* accompanying the pulse of 5-kev precipitating electrons. Since the rocket was at an altitude of over 700 km at the time, such electrons would have taken  $\sim 100$  msec to travel up from a  $\sim 200$ -km source altitude. In fact (Table 3), they were present less than 10 msec after the pulse, with no time dispersion at all. We therefore conclude that this upsurge, although statistically significant at the 99.9% level, cannot be explained as backscattered electrons whose intensity increased because of the pulse of 5-kev electrons precipitated.

We have paid particular attention to this pulse in Twins 2B, because it is the only isolated pulse seen in the data to date. Yet it is undoubtedly a real effect (see Appendix 1). A comparably large pulse of 200 counts occurred in Twins 2B some 8 sec earlier accompanied by nearby pulses of 58 and 85 counts, and, of course, with pulses in Twins 2A (Figure 8). It is interesting to note that in this instance the upflux of electrons seen by channels 1, 2, and 5 at the same voltage level in the frames around the modulation peaks was very close to the 49-frame averages, and thus our concept that the apparent enhancement of Table 3 was due to chance is reinforced. This relationship is also observed for other bursts we have studied.

Since pulses have been found at all voltage settings of SPECS (see Appendix 1), we have been able to examine the related behavior of electrons over the complete energy range. In no instance were we able to detect consistently significant effects for different pulses, other than the pitch-angle distribution discussed above.

#### TEMPORAL VARIATIONS

We have also examined the temporal variation in the development and progress of the modulation effects, and again no definite pattern has appeared. For example, on a given Twin there may be one large isolated modulation (Figure 2), a few isolated modulations (Figure 8), or a long train of modulations lasting several seconds (Figure 3). Whereas the low DED on

Twins 2A appears a little more sensitive to the modulation than that on Twins 2B (which has a slightly higher-energy passband as in Table 1), it does appear that, whenever modulations are seen by 2B, they are present in 2A data also. Separation of the two payloads ranges up to  $\sim 1$  km in the plane orthogonal to *B*, and the preliminary survey does not reveal any marked deviation from the above at any separation. However, a lengthy cross-correlation study is underway to examine these findings precisely, and at this stage we use only clear-cut isolated bursts, such as those of Figures 2 and 8, to justify the statement that the effect is seen simultaneously at separations (perpendicular to *B*) of up to  $\sim 1$  km. If the effect had been a purely spatial one, i.e., if the two payloads had passed successively through a single stationary spatial structure, Twins 2A would have observed it about 1 sec before Twins 2B.

Of course, the possibility remains that the simultaneous enhancements were due to spatial structures moving relative to the trajectory of the payloads. For the leading edge of such structures to arrive at the two payloads separated by 1 km within the minimum resolvable time of 0.05 sec, the velocity of the structures relative to the payloads would have to be at least 20 km/sec. (Recall that the absolute velocity of the payloads orthogonal to *B* was 0.5 km/sec.) The effects could also be produced by spatial structures nearly aligned with and moving normal to the trajectory of the payloads. Although we concede that such situations could exist, it must be understood that there could have been no stationary spatial structures, for no time delays on the order of 1 sec were seen. Therefore, if one assumes that the effects were due to spatial structures, one must assume an extremely fortuitous combination of structure orientation and velocity, a situation that seems highly unlikely. We therefore argue that the enhancements are truly temporal in origin.

In summary, we have proven that, on occasions sometimes as short as  $\leq 0.1$  sec but sometimes for several seconds, there is an  $\sim 10$ -fold increase in the flux of precipitated 5-kev electrons in a very narrow range of  $\alpha \leq 10^\circ$ . The effect is seen simultaneously at altitudes of up to  $\sim 800$  km by two payloads up to 1 km laterally distant from one another. To first order, the remaining auroral electrons display

no significant change in pitch angle.

#### SUMMARY OF EVIDENCE

To summarize the evidence for the enhancements of the flux of 5-kev electrons with pitch angles  $\alpha \leq 10^\circ$  found to occur sporadically at altitudes up to 800 km. Since the



Fig. 8. Similar data were obtained in the interim.

no significant change in energy spectrum or pitch angle.

### SUMMARY OF EXPERIMENTAL RESULTS

To summarize the preceding sections, 10-fold enhancements of the flux of 5-keV auroral electrons with pitch angles  $\alpha < 10^\circ$  have been found to occur sporadically at altitudes of up to 500 km. Since the enhancements are seen

simultaneously by two rocket payloads at separations of up to  $\sim 1$  km, they were temporal in origin, lasting for  $< 0.1$  sec up to several seconds. Also no significant relation to these bursts could be found in either the flux of electrons with the same pitch angles ( $\alpha \leq 10^\circ$ ) but with energy of  $\sim 12$  keV or the flux of electrons with energy of  $\sim 40$  eV to 100 keV at  $30^\circ \leq \alpha \leq 60^\circ$ . Such phenomenon places quite extraordinary

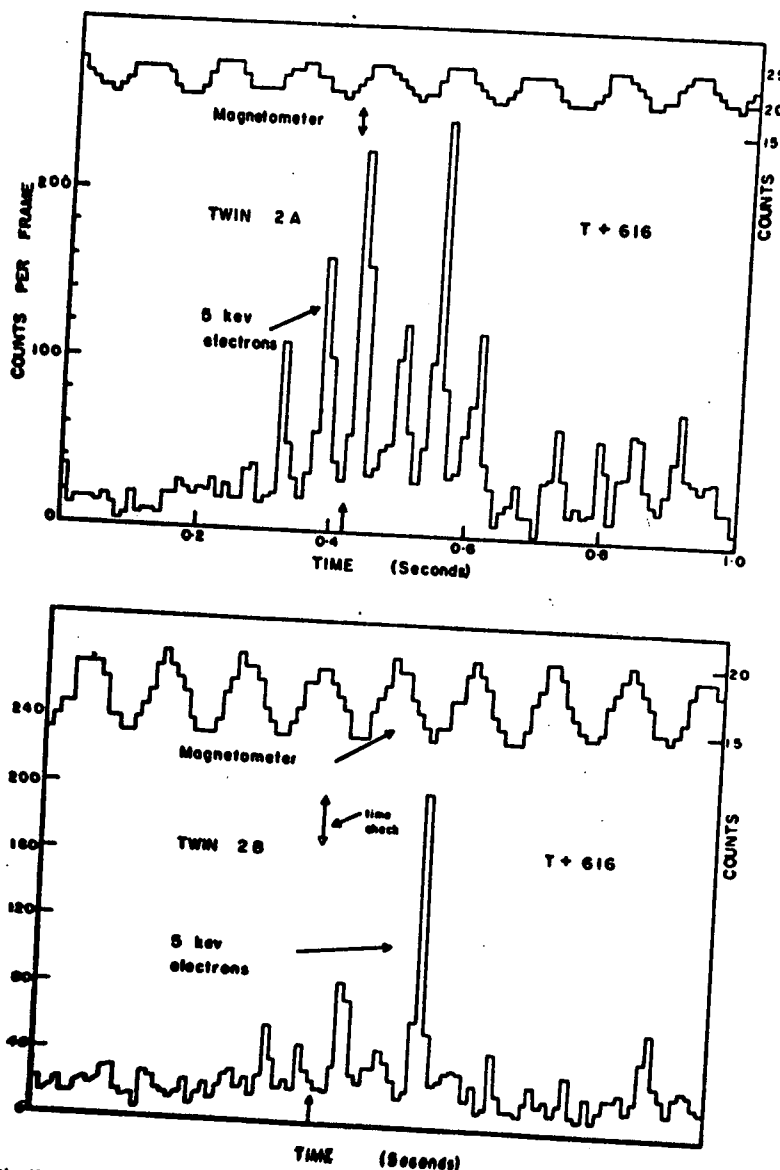


Fig. 8. Similar to Figure 2 but showing enhancement for a slightly longer time. These data were obtained about 8 sec before those of Figure 2, but there were no enhancements in the interim.

constraints on any postulated mechanism of auroral acceleration, and we now discuss the relevance of this finding to existing auroral theories. We refer to this phenomenon as a burst and its characteristics are summarized in Table 4.

#### CONFINEMENT TO SMALL PITCH ANGLES

If we consider either a short-duration or a long-duration burst (see Figures 2 and 3), we find a remarkable pitch-angle distribution of 5-keV electrons, shown here as Figure 9. The extent of the confinement to very small values of  $\alpha$ , i.e., near-parallel to the geomagnetic field  $B$  is quite extreme. For example, the count rate of the low DED sensor falls by a factor of 2 when it samples 5-keV electrons with  $12^\circ \leq \alpha \leq 15^\circ$  instead of  $1^\circ \leq \alpha \leq 19^\circ$ , and we have concluded that the peak flux is at  $\alpha \leq 10^\circ$ . In other bursts, the modulation factor (which is a factor of  $\sim 2$  in Figure 8) is as large as a factor of 10, and thus the confinement to near  $B$  is even more extreme (Figure 10).

As seen in Figures 9 and 10, therefore, the flux of electrons with energy  $E \sim 5$  keV has a pitch-angle distribution with a broad maximum at  $\alpha \geq 60^\circ$  and a very narrow maximum at  $\alpha \leq 10^\circ$ . By contrast (Figure 9), the flux of very-low-energy electrons (40–50 eV) has a maximum only at  $\alpha \leq 30^\circ$ . This feature is important and is discussed later.

We should add that three other groups [Riedler, 1966; Lampton *et al.*, 1967; Hoffman and Evans, 1968] also reported fluxes peaked at small pitch-angles. However, because those studies had neither the capability of separating spatial from temporal effects nor of studying electrons with energy down to  $\sim 40$  eV, only with the Twins 2 data can we examine the effect more accurately and indeed show some

previous interpretations to be in error (see below).

#### TEMPORAL EXTENT OF THE BURSTS

Although the bursts may persist for up to  $\sim 10$  sec, one occurred with a duration of  $\leq 0.1$  sec (see Figures 2 and 3). If one assumes that the electrons responsible had energies over much of each low DED passband (namely 3.7–6.7 keV and 4.0–7.6 keV), as is indicated by the fact that both the slightly different sensors detected the bursts, this short-duration pulse is extremely interesting. The velocities of the electrons at the lower and higher edges of the energy passband are, respectively,

$$V_1 \sim 3.5 \times 10^9 \text{ cm/sec}$$

and

$$V_2 \sim 5 \times 10^9 \text{ cm/sec}$$

Hence, for the electrons to arrive at the rocket payload simultaneously within  $< 0.1$  sec, if they were initially 'produced' at the same time and place, that location must be less than about 5000 km above the rocket.

The rocket at the time of this short burst was near its peak altitude of 800 km. Thus, given the above assumptions, the 'source' would have to have been at an altitude of  $\lesssim 6000$  km. To test this further, we sought such short-lived bursts in the lower-altitude data. Unfortunately, although the strong spin-modulation due to the fan-shaped off-center detector was still present on occasions, indicating peak fluxes at  $\alpha \leq 10^\circ$ , at no time was the modulation as brief as in the burst of  $T + 624$  sec (Figure 10). Thus this one example remains. Since the envelope of the burst is not precisely defined, we will generally argue for a source altitude of  $\lesssim 1 R_E$ , given the above assumptions. We discuss this further below and compare it with estimates made by others.

With the source altitude of  $\lesssim 1 R_E$ , the count rate of the high DED sensor of  $\sim 12$ -keV electrons would be expected to have detected the burst some 50 msec or 5 telemetry frames earlier, given the usual assumptions of simultaneous acceleration at the same source. In fact, there was no detectable effect at all.

In a general consideration of the temporal nature of bursts, which is of course the en-

TABLE 4. Characteristics of a Burst

Duration	$\leq 0.1$ up to $\sim 10$ sec
Electron energy	$(5 \pm 1)$ keV and less frequently 12 keV
Pitch angle	$\alpha < 10^\circ$
Altitude of detection	$\sim 250$ up to 800 km
Associated changes in other electrons	None found consistently to date
Spatial extent	At least 1 km orthogonal to $B$ over Fort Churchill

velope of the sp  
rates, we are co  
that there is a  
the responses o  
payloads. Thes  
First, the lo  
prone to show  
low DED on  
ures 2 and 8).  
sensor showed  
the spin rate,

velope of the spin-induced modulation of count rates, we are confronted at once with the fact that there is a slight but definite difference in the responses of the similar sensors on the two payloads. These differences were of two types.

First, the low DED on Twin 2A was more prone to show strong spin modulation than the low DED on Twin 2B (for example, see Figures 2 and 8). Second, whereas the Twin 2A sensor showed nearly equal modulation at twice the spin rate, the modulation on Twin 2B was

definitely unequal, with a more pronounced maximum when the magnetometer count rate (and hence pitch angle) was a minimum.

Because we have already seen how closely collimated the bursts are (Figures 9 and 10 and discussion), we believe that these differences arise from slight ( $\sim 1^\circ$  to  $2^\circ$ ) differences in the angular responses and mechanical mounting of the two sensors. It may be noted, for example, that in-flight calibration of the magnetometers implied that the Twin 2A rocket axis was about

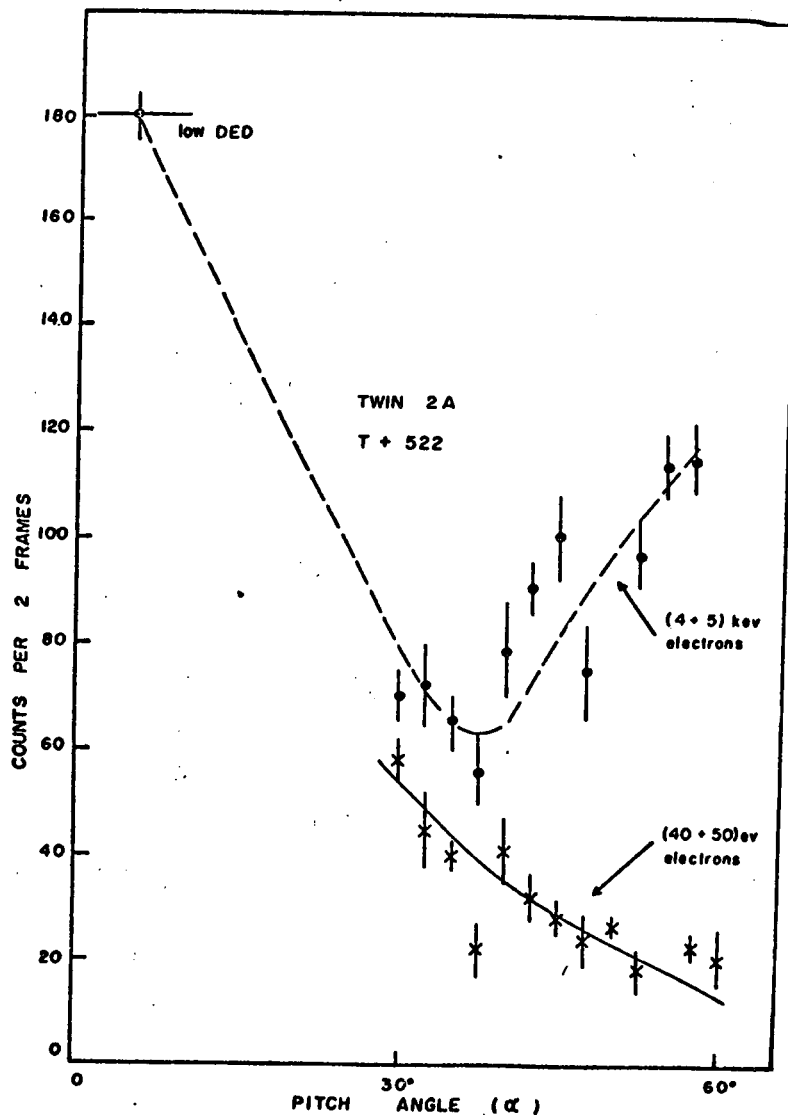


Fig. 9. Pitch-angle distribution of low-energy (40 and 50 ev) and medium-energy (4 and 5 kev) auroral electrons.

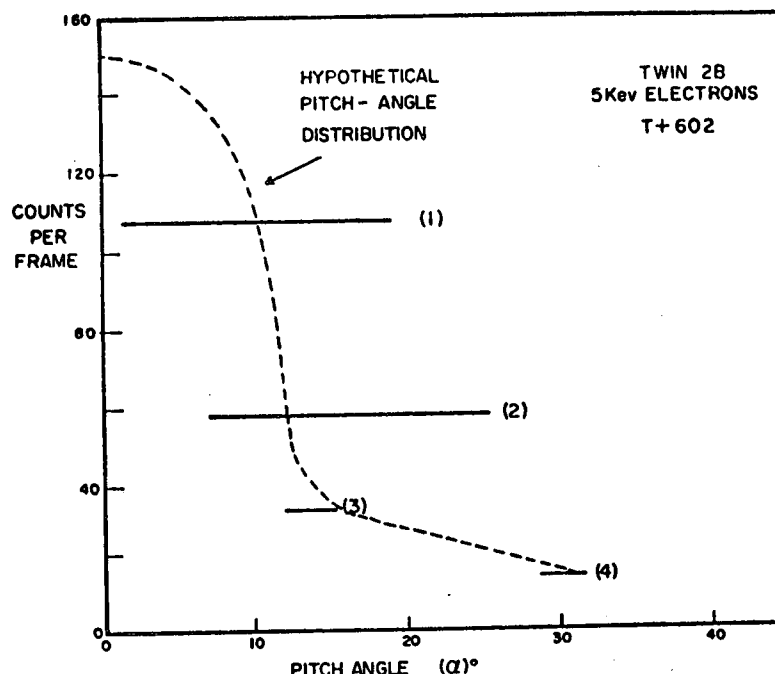


Fig. 10. Pitch-angle distribution during an auroral burst of 5-keV electrons. As the rocket spun, the off-axis wedged-shaped response of the low DED caused it to sample electrons over the ranges shown, namely (a)  $1^{\circ}$ – $19^{\circ}$ , (b)  $7^{\circ}$ – $25^{\circ}$ , and (c)  $12^{\circ}$ – $15^{\circ}$ . The SPECS instrument gave the value shown (d) at  $\alpha \sim 30^{\circ}$ . The hypothetical pitch-angle distribution is derived by combining all the measurements.

$2^{\circ}$  closer to  $B$  than was that of Twin 2B. A similar difference, in the same sense, was found on the Twin 1 flight [Westerlund, 1968]. Since there was negligible coning, these angles must actually be the same, and thus we can assert a possible sensor alignment error of  $\sim 2^{\circ}$  in the correct sense for the observed differences in the responses. Since the bursts studied were of low-energy electrons, there may also have been an increased sensitivity of the Twin 2A sensor because its energy passband was of slightly lower energy.

Given the above conditions, we have found no consistent pattern of growth, duration, and decay of the bursts. Whatever the cause, the burst must be capable of lasting as short a time as  $\leq 0.1$  sec or as long a time as  $\sim 10$  sec. The burst was quite a common feature of the Twins 2 flight, and, just from visible scanning of the data, it is prominent in at least 10% of the data.

#### ELECTRON SPECTRA

The electron spectra averaged over pitch angles  $30^{\circ} \leq \alpha \leq 60^{\circ}$  ranged during the flight over the limits shown in Figure 11. This figure is derived by considering the maximum and minimum 49-frame ( $\approx 0.5$  sec) sums of counts from each channel. The individual spectrum during a 3.6-sec scan can be extremely complex and can have two clear peaks, one at say  $E \sim 50$  ev and the other at  $E \sim 7$  kev, or it may just have the 'continuum' spectrum discussed by Westerlund [1969] with a clear maximum in the range from 40 to 50 ev and merely a slight inflection in the vicinity of a few kiloelectron volts.

We have not been able to discern any consistent pattern of association of one particular spectral form with bursts, except for the fact that bursts of  $\sim 5$ -kev or  $\sim 12$ -kev electrons at  $\alpha \leq 10^{\circ}$  are found only in association with electrons with  $30^{\circ} \leq \alpha \leq 60^{\circ}$ , which indeed

have spectra energies. In cident when the angles is of t must be em 'auroral' spect few kiloelectro there were oc trons at  $\alpha \leq$  effect at  $\sim 5^{\circ}$

We conclude an auroral pe electron volt probably a r tion for bur that this co weight beca was present, low, and un the rapidly was necessa

#### VARIATION

Figure 9 pitch-angle and low-en bursts, the mums at  $\alpha$  low-energy  $30^{\circ}$ . There but here v this partic

Accordin like the al model of to such te

Chamb whereby able to p a line of tial drop the initia cording tion, th energies have a isotropic pitch ticles w This fir periods 9), and

have spectra with high intensities at these energies. In other words, bursts are not evident when the electron spectrum at larger pitch angles is of the continuum type. However, it must be emphasized that there were many 'auroral' spectra, i.e., with a strong peak at a few kiloelectron volts at  $30^\circ \leq \alpha \leq 60^\circ$ , when there were occasionally bursts of  $\sim 12$ -keV electrons at  $\alpha \leq 10^\circ$  without any accompanying effect at  $\sim 5$  keV.

We conclude, therefore, that the presence of an auroral peak in the spectrum at several kiloelectron volt energy and  $30^\circ \leq \alpha \leq 60^\circ$  is probably a necessary but not sufficient condition for bursts to be found. We do not believe that this conclusion should be given undue weight because, when the continuum spectrum was present, the count rate of the low DED was low, and unambiguous detection of a burst in the rapidly varying small counts of the sensor was necessarily difficult.

#### VARIATION OF SPECTRA WITH PITCH ANGLE

Figure 9 clearly shows the typically different pitch-angle dependence of auroral ( $\sim 5$  keV) and low-energy ( $\sim 50$  eV) electrons. During bursts, the auroral electrons may have maximums at  $\alpha \leq 10^\circ$  and at  $\alpha \geq 60^\circ$ , whereas the low-energy electrons have a maximum at  $\alpha \leq 30^\circ$ . There are considerable variations in detail, but here we wish to discuss the implications of this particular spectral pitch-angle variation.

According to Chamberlain [1969], knowledge like the above could be used to 'test any given model of electric acceleration.' We now proceed to such tests.

Chamberlain [1969] considers a mechanism whereby a weak parallel electrostatic field is able to precipitate particles initially trapped on a line of force. In this calculation, the potential drop was assumed to be small relative to the initial kinetic energies of the particles. According to the results of Chamberlain's calculation, the lowest energy particles, those with energies comparable to the potential drop, would have a pitch-angle distribution more or less isotropic with a tendency to be peaked at small pitch angles, whereas the higher-energy particles would be peaked at larger pitch angles. This finding is in agreement with our data for periods when no bursts are present (see Figure 9), and therefore a small potential drop ( $\sim 40$

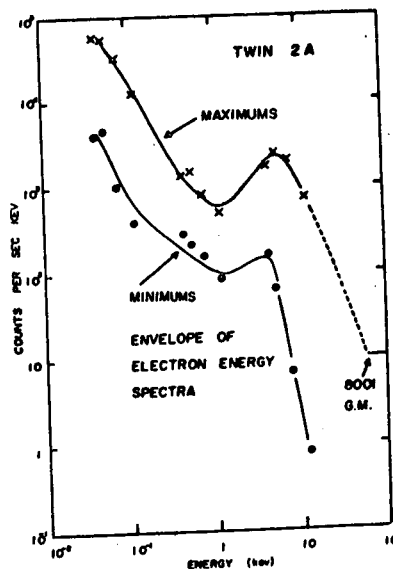


Fig. 11. Range of energy spectra encountered on the Twins 2 flight for  $30^\circ \leq \alpha \leq 60^\circ$ .

volts) could explain the situation in which the low-energy electrons ( $\sim 50$  eV) are peaked at small pitch angles and the higher-energy electrons ( $\sim 5$  keV) are peaked at larger pitch angles. However, if one wishes to extend this mechanism to explain the field-aligned bursts of high-energy electrons, one must assume a potential drop on the order of 5 kV or greater to account for the extreme collimation of the 5-keV electrons. However, such a large potential drop would also drastically reduce the flux of lower-energy electrons and at the same time increase the flux of higher-energy electrons ( $> 10$  keV) at large pitch angles. In fact, neither of these effects are observed in our data. In summary, we can explain the pitch-angle distributions of the electrons in the absence of bursts by a small potential drop ( $\sim 40$  volt) along the field lines, but we are unable to explain the bursts by appealing to a much stronger transient potential drop because we do not observe corresponding effects on electrons at other energies.

It is interesting to examine the bursts in the light of Perkins's [1968] study of plasma-wave instabilities above an aurora. Perkins predicted that, if the 'monoenergetic' auroral electron flux were to grow above  $\sim 7 \times 10^9$  particles  $\text{cm}^{-2} \text{sec}^{-1} \text{ster}^{-1}$  at  $\alpha \sim 90^\circ$ , electrostatic plasma

waves could 'grow to an amplitude large enough to cause stochastic acceleration of a few electrons to energies of  $\sim 40 - 100$  kev on a time scale of  $\sim 10^{-2}$  sec.' Perkins intended his studies to be applicable to the breakup phase of an aurora, which was not true for the Twins 2 flight, but it still appears to be useful to examine briefly the possible role of this mechanism.

First, since we did not examine electrons at  $\alpha = 90^\circ$ , we are not in a position to determine whether the critical flux was reached. From study of the data, we believe, however, that the flux was generally less than  $10^6$  particles  $\text{cm}^{-2} \text{sec}^{-1} \text{ster}^{-1}$  in the range from 1 to 10 kev. However, let us suppose that it did reach the necessary critical level, whether or not it was the specified figure. Perkins [1968] estimates a growth rate on a time scale of the order of 10 msec, and that certainly satisfied our minimum observed time scale of  $\sim 100$  msec. Let us also assume that somehow the process is capable of enduring for up to  $\sim 10$  sec with no perceptible damping or effect on the  $\sim 12$ -kev electrons or any electrons in the  $30^\circ \leq \alpha \leq 60^\circ$  range.

However, there are two unassailable criticisms of the applicability here of the process envisaged by Perkins [1968]. First, he predicts that 'the very energetic downgoing electrons should be produced roughly isotropically but with a weak concentration of pitch angles towards  $90^\circ$ .' Our Figures 9 and 10 refute this prediction. Second, Perkins predicts that 'the upwards-going very energetic electrons (should have) the pitch-angle distribution peak at  $180^\circ$ .' Our data shown above refutes this completely. In fact, the data are much more in accord with what one might call an 'upside-down' Perkins process with peak flux at  $\alpha \leq 10^\circ$  rather than at  $\alpha \sim 180^\circ$ . However, such an upside-down process is, according to Perkins, not physically realizable when one considers the direction of propagation for which amplification of the wave packets will occur. In addition, of course, the occurrence of bursts over the altitude range of  $\sim 200$  to  $\sim 800$  km, with no clear-cut differences, poses a problem for any process so dependent on local ionospheric properties.

Another theoretical model is that of Speiser [1965], wherein a small transverse  $B$  in the magnetotail causes ejection of particles energized in their drift across the postulated electro-

static potential. However, as pointed out by many others [Sonnnett *et al.*, 1967; Hoffman and Evans, 1968] the magnetotail magnetic field is measured to be quite different from that assumed by Speiser [1965]. Second, the extreme collimation we observe in the bursts make it seem very unlikely that they could have traveled such great distances [see Speiser, 1967], as does their occasional short duration (see above).

#### FIELD-LINE MERGING

It is apparent from the above discussions that the theories or models treated [see O'Brien, 1967] cannot account for our observations. Nor can the observations be ignored because we have shown that they are consistent with, and merely more detailed than, other independent experiments [Hoffman and Evans, 1968; Riedler, 1966; Lampton *et al.*, 1967] and the previous Twins 1 study [Westerlund, 1969]. Thus, for example, Westerlund [1969] found the preference of the  $\sim 50$ -ev electrons to have one maximum at  $\alpha \leq 30^\circ$ , but he was not in a position to clearly detect the bursts of more energetic electrons. On the other hand, Hoffman and Evans [1968] found the field-aligned bursts, but they were unable to measure pitch-angle distributions of lower-energy electrons or, for that matter, to prove that the bursts were temporal. Thus we need another explanation of the observations. One proposed source of energization of auroral particles is the dissipation of magnetic energy involved when geomagnetic-field lines merge [see Azford, 1969; Piddington, 1968]. However, analysis of the conditions for merging of geomagnetic with interplanetary-field lines or reconnection of geomagnetic-field lines is extremely complex and, to our knowledge, imperfectly understood. We now will set up post hoc conditions for the source mechanisms, and then briefly examine whether these can be applicable to magnetic-field merging.

The source(s) of electrons must be able to explain the following types of fluxes:

1. A continuum flux extending more-or-less monotonically from a peak at  $\sim 40$  ev up to energies of  $\geq 20$  kev, which is generally present at night over Fort Churchill, with considerable fluctuations in intensities at given energies. This continuum has a pitch-angle distribution that

is peaked at  $\alpha \leq 30^\circ$  for  $\alpha \leq 30^\circ$  and at  $\alpha \geq 60^\circ$  for  $\alpha \geq 60^\circ$  (see Figure 10). The continuum changes over the altitude range  $200$  to  $800$  km, but over the invariant latitude range  $70^\circ \leq \Lambda \leq 73^\circ$  [see Speiser, 1962].

2. An auroral spectrum of electrons primarily with energies  $\geq 40$  ev, which is greatly enhanced and superposed on the continuum during the rocket flight. The 4- and 5-kev electrons have an energy varied by  $\sim 3500$  ev, with no discernible systematic structure. The spectrum can have the following distribution: (a) isotropic, (b) anisotropic with one maximum at  $\alpha \leq 30^\circ$  and (c) anisotropic with one maximum at  $\alpha \geq 60^\circ$  and another, a burst characteristic of a burst at  $\alpha \sim 90^\circ$ .

Now, in agreement with the observations, we used Twins 1 data to show that the continuum to be consistent with either of the thermalized electron spectra found in the magnetotail. The spectra of the plasma sheet, the Twins 2 showed a change in the peak intensity. We consider the early (see below). Energy spectra of Frank [1968] and Berman [1968] in the magnetosheath and [1968] in the plasma sheet of the continuum, with all do display considerable variation (see below).

We believe the auroral energies concentrated in the bursts, to be due to pitch-angle diffusion, Kennel [1969]. When they received their energy in the ionosphere, the ionospheric ionization or from 'fast ionospheric ionization' unknown to us and, however, it does seem that they are trapped in the sense of field lines because they are of high intensity outside the ionosphere at  $800$ -km altitude).



as pointed out by 1967; Hoffman and tail magnetic field is different from that [i]. Second, the ex- e in the bursts make at they could have nces [see Speiser, onal short duration

# MERGING

e above discussions eated [see O'Brien, r observations. Nor red because we have nt with, and merely independent experi- ns, 1968; Riedler, ] and the previous l, 1969]. Thus, for ] found the prefer- s to have one maxi- as not in a position of more energetic and, Hoffman and ield-aligned bursts, measure pitch-angle y electrons or, for e bursts were tem- explanation of the source of energiza- the dissipation of when geomagnetic- , 1969; Piddington, the conditions for ith interplanetary- f geomagnetic-field and, to our knowl- l. We now will set the source mecha- ine whether these ic-field merging. s must be able to f fluxes:

ending more-or-less at  $\sim 40$  ev up to s generally present with considerable ven energies. This : distribution that

is peaked at  $\alpha \leq 30^\circ$  for low energies (40–100 ev) and at  $\alpha \geq 60^\circ$  for medium energies (1–10 kev). The continuum displays no systematic change over the altitude range of  $\sim 200$ –800 km nor over the invariant latitude range [O'Brien, 1962] of  $70^\circ \leq \Lambda \leq 73^\circ$ .

2. An auroral spectrum in which the flux of electrons primarily with energies of  $\sim 5$  kev is greatly enhanced and apparently superimposed on the continuum. The narrowness of this auroral spectrum can be gaged by the fact that, during the rocket flight, the ratio of fluxes of 4- and 5-kev electrons only 20% different in energy varied by 3500%, but again there was no discernible systematic pattern. The auroral spectrum can have three types of pitch-angle distribution (a) isotropic for  $0^\circ \leq \alpha \leq 60^\circ$ , (b) anisotropic with one maximum at  $\alpha \geq 60^\circ$ , and (c) anisotropic with one maximum at  $\alpha \geq 60^\circ$  and another, a burst, at  $\alpha \leq 10^\circ$ . The characteristics of a burst are given in Table 4.

Now, in agreement with Westerlund [1968], who used Twins 1 data, we believe the continuum to be consistent with characteristics either of the thermalized solar wind, which is found in the magnetosheath, or of electron spectra of the plasma sheet. (Unlike Twins 1, the Twins 2 showed no systematic latitude change in the peak in the  $\sim 100$ -ev range, so we consider the early Twins 1 finding fortuitous.) Energy spectra such as those found by Frank [1968] and Bame et al. [1967] in the magnetosheath and by Montgomery et al. [1968] in the plasma sheet are similar to those of the continuum, with the understanding that all do display considerable variations in detail (see below).

We believe the auroral spectrum (fluxes with energies concentrated at 1–10 kev), apart from the bursts, to be due to moderate or strong pitch-angle diffusion, such as that discussed by Kennel [1969]. Whether these electrons received their energy in the actual energy diffusion accompanying the intense pitch-angle diffusion or from 'fast ionospheric instabilities' is unknown to us and to Kennel [1969]. However, it does seem that they are at least quasi-trapped in the sense of being on 'closed' field lines because they can have a maximum intensity outside the loss cone (namely  $\alpha \geq 60^\circ$  at 800-km altitude). This assumption is also

consistent with the observed magnetic conjugacy of relatively quiet auroras [Belon et al., 1969], such as the one studied with Twins 2.

Now the important point is that these same quasi-trapped auroral electrons can be present on the same field lines as the continuum. Since we do not see how this situation could physically exist if the continuum consisted of magnetosheath particles, it seems that these continuum electrons most likely came from the plasma sheet.

This concept tends to be validated by the fact that a secondary maximum in the energy spectrum in the range from 1 to 10 kev was reported by Montgomery et al. [1968] for the plasma sheet but not, to our knowledge, for the magnetosheath. Thus this finding would correspond to our Twins 2 continuum plus auroral spectrum of type a or b (see above). We therefore tentatively conclude that when the Twins 2 observed anything except the field-aligned bursts, they were on closed field lines that passed through the plasma sheet on which occasional strong diffusion processes [see Kennel, 1969] caused increased precipitation. The tendency for the low-energy electrons ( $\sim 40$ –100 ev) to be most intense at  $\alpha \leq 30^\circ$  is examined further in the light of this notion below. We think that it is most plausible that the field lines are also closed during bursts, but we cannot prove that they are.

Now we examine the cause of the bursts. Axford [1969] has noted that, if an electron is able to make many traversals of the entire field line during the rapid contraction of the field lines after reconnection, they will take on a pitch-angle distribution peaked along the magnetic-field direction. But our observation of bursts of only  $\sim 0.1$ -sec duration implied source altitudes of  $\leq 1 R_s$ . Furthermore, as we stated above, the flux of electrons at  $30^\circ \leq \alpha \leq 60^\circ$  remains apparently unaffected during a burst, whereas any such field-line shrinking would greatly affect both the pitch-angle and energy distributions of these particles. In this sense, then, where we have the opportunity to test an explicit prediction of the consequences of field-line merging, we find it to be inadequate. Thus once more we must reject a postulated cause of the effects we noted. (We should emphasize that we are seeking only to explain the observed phenomena

and, of course, cannot say that one or another of the postulated source mechanisms never occurs.)

#### DISCUSSION

We examined the various postulated acceleration/precipitation processes known to us and found each individually to be inadequate. We now briefly examine the adequacy of a mixture of several processes.

The following processes may occur. First, thermalized solar wind can, on occasion, gain access to the plasma sheet, thus giving it the continuum electron population. This process must be quite common, because, as we have discussed elsewhere [O'Brien, 1970], with the electron content of the order of  $10^{14}$  particles in a tube of force through  $1 \text{ cm}^2$  at 800 km above Fort Churchill, the observed precipitation  $10^{10}$  to  $10^{11}$  electrons/ $\text{cm}^2 \text{ sec}$  would completely drain such a tube in some  $10^4$  to  $10^5$  sec. The rocket flight time was of the order of  $10^3$  sec, and appreciable precipitation of at least  $10^9$  particles/ $\text{cm}^2 \text{ sec}$  was observed throughout. The visible auroral display also continued for several hours. It is apparent then that auroral-particle depletion of the ambient plasma in the outer regions of the magnetosphere poses a complex problem of replenishment.

Since the backscattered (i.e., upmoving) flux of electrons above 40 ev was measured to be only of the order of 10% of the precipitated flux, any significant replenishment by backscattered electrons must be by those with energy  $E \lesssim 40$  ev. It would thus be relatively slow, with a 10-ev electron taking tens of seconds to reach the equator. Nevertheless, such a return current could suffice, although an initial large surge might fade away through this depletion.

It is often suggested [Azford, 1969; Pidington, 1968] that convection of 'new' tubes of force across the polar cap will bring new supplies of plasma to the aurora. However, because one frequently can observe long multiple east-west arcs with no significant latitudinal variation of intensity and persisting for hours [Chamberlain, 1961], it is difficult to see how this resolves the depletion problem we discussed. Indeed, even if one turns to an external source of electrons, such as the solar

wind, one can only just satisfy the particle demand. We have shown elsewhere [O'Brien, 1964] that the energy dissipated in the aurora world wide is, on the average, about 1% of the energy brought by the solar wind to the magnetosheath. By a comparable calculation one can show that the worldwide deposition of auroral electrons into the atmosphere is of the order of 10% of the incident flux of solar-wind electrons. (A simple way to relate the energy and flux percentages is to compare the average solar-wind proton energy of  $\sim 1$  kev with the average auroral-electron energy of  $\sim 100$  ev.)

In the context of the above discussion, it appears to us to be most likely that the major source of replenishment of electrons in auroral tubes of force is the flux of backscattered electrons with energies of the order of 1 to 10 ev. The role of convection would be then in smearing this upflux over many 'tubes of force.' If this is the situation, it implies that a particularly bright auroral form at a given location should be of short duration, although it may well be repeated in some tens of seconds.

Let us suppose then that, for some 1-10% of the time, the plasma sheet is populated by solar-wind electrons through direct connection with interplanetary-field lines. The rest of the time the field lines are closed. Of course, they might always be closed with particle population furnished by an  $\mathbf{E} \times \mathbf{B}$  drift.

We further suppose that a Taylor-Hones acceleration mechanism can occur, but it occurs in a microscopic extremely variable manner. Thus the magnetospheric structure averaged over time is like the Taylor-Hones equipotential pattern, but at any instant positive or negative potential differences of kilovolts between neighboring tubes of force may exist. This would explain the extreme variability of the flux of 1 to 20 kev, which had no discernable latitudinal dependence.

We then need moderate diffusion processes [Kennel, 1969] to precipitate the continuum and then change to strong diffusion when the more energetic electrons are present. Alternatively, of course, as Kennel [1969] comments 'the high-energy tail (caused by strong diffusion) can be more extensive than in weak diffusion.'

To produce the  $\alpha \leq 30^\circ$ , we predict a potential drop ( $\sim 10^4$  v) in the magnetic-field line up must extend to v. the depletion rate order of a few m

But we had been to explain the but liberty we took w and current system was the shortest-applied limitation of  $R_s$ . We have el origin because it two payloads  $\sim 1$  seconds before a bursts. Because fluxes, it is difficult that the simultaneous by both payloads each merely happen through two sm ( $\sim 50$  meters diameter electron does not appear cause the region order of a few cause we have other events of In spite of these although small, theory can explain discussed above explain it presumably

However, we indicate that our may be valid measure the time at a rocket of thus to deduce 1967a, 1967b; all indicated a ments were based on observations of spatial origin; support our findings

Accordingly, 'explain' the merging and occurring at  $73^\circ$  at altitudes

to satisfy the particle  
elsewhere [O'Brien,  
dissipated in the aurora;  
average, about 1% of  
the solar wind to the  
comparable calculation,  
worldwide deposition  
the atmosphere is of  
incident flux of solar-  
leeway to relate the  
res is to compare the  
an energy of  $\sim 1$  keV  
al-electron energy of

above discussion, it  
likely that the major  
f electrons in auroral  
flux of backscattered  
the order of 1 to 10  
on would be then in  
er many 'tubes of  
ation, it implies that  
oral form at a given  
rt duration, although  
d in some tens of

t, for some 1-10% of  
is populated by so ar-  
rect connection with  
The rest of the time  
f course, they might  
article population fur-

a Taylor-Hones ac-  
occur, but it occurs  
ly variable manner.  
structure averaged  
-Hones equipotential  
positive or negative  
volts between neigh-  
exist. This would ex-  
ity of the flux of 1  
iscernable latitudinal

e diffusion processes  
itate the continuum  
y diffusion when the  
re present. Alterna-  
al [1969] comments  
ed by strong diffu-  
than in weak diffu-

To produce the low-energy electron peak at  
 $\alpha \leq 30^\circ$ , we presumably should add a small  
potential drop ( $\sim 40$  volts) along the geomag-  
netic-field line up toward the plasma sheet. It  
must extend to very high altitudes to satisfy  
the depletion rate. It could thus be of the  
order of a few microvolts per meter or less.

But we had been unable to set up a model  
to explain the bursts, no matter how much  
liberty we took with magnetospheric topology  
and current systems. A major stumbling block  
was the shortest-duration burst, with its im-  
plied limitation of the source altitude to  $\leq 1$   
 $R_E$ . We have claimed it to be temporal in  
origin because it was seen simultaneously by  
two payloads  $\sim 1$  km apart, whereas for several  
seconds before and after there were no such  
bursts. Because of the great variability of the  
fluxes, it is difficult to assess the probability  
that the simultaneous detection of this burst  
by both payloads was due to chance and that  
each merely happened to pass simultaneously  
through two small spatially localized regions  
( $\sim 50$  meters diameter) where a highly colli-  
mated electron flux was present. This event  
does not appear to be very likely, both be-  
cause the region would have to be only of the  
order of a few cyclotron diameters and be-  
cause we have simultaneously seen several  
other events of only  $\sim 0.1$ - to  $0.2$ -sec duration.  
In spite of these factors, the possibility is real,  
although small, and, if an otherwise acceptable  
theory can explain all the observations dis-  
cussed above except for the altitude limitation,  
it presumably should be accepted temporarily.

However, we have further relevant data that  
indicate that our altitude restriction to  $\leq 1$   
 $R_E$  may be valid. When attempts were made to  
measure the time delays between the 'arrival'  
at a rocket of electrons of several energies and  
thus to deduce a source altitude [Evans, 1966,  
1967a, 1967b; Lampton, 1967; Winiecki, 1967],  
all indicated a source of  $\leq 1$   $R_E$ . Those experi-  
ments were based on the assumption that varia-  
tions observed were of temporal rather than  
spatial origin; nevertheless, they do tend to  
support our finding.

Accordingly, although we might prefer to  
'explain' the bursts as being due to field-line  
merging and contraction, the necessity for this  
occurring at various latitudes between  $71^\circ$  and  
 $73^\circ$  at altitudes of  $\leq 1$   $R_E$  seems to us to place

untenable requirements on magnetospheric  
topology.

#### PRACTICAL IMPLICATIONS OF THESE RESULTS

Some additional interesting and nontrivial  
implications of this study are now mentioned  
briefly. We have proven basically that the  
flux of auroral electrons at  $\alpha \sim 0^\circ$  can be  
enhanced with no appreciable effect on the  
flux at larger pitch angles. With a smaller  $\alpha$ ,  
an electron of a given energy will, of course,  
penetrate deeper into the atmosphere. Yet  
many studies equate deeper penetration with  
a higher energy and neglect this pitch-angle  
dependence.

To cite one example, we discuss Eather's  
[1969] study of O I (6300-Å) pulsations. From  
the interrelation of pulse rate and quenching  
times, Eather concludes that the faster pulsa-  
tions ( $\sim 1$ -5 sec) are associated with higher-  
energy electrons. In fact, he states that 'this  
should be an integral feature of any theory  
of pulsations.' This conclusion is based on a  
peak O I emission at  $\sim 97$  km versus 118 km.  
Of course, such an extended atmospheric pene-  
tration is readily achieved with a particle of  
the same energy but smaller pitch angle (such  
as reported here), and thus we presently see  
no need to make such energy-period depen-  
dence a prerequisite of satisfying auroral  
theories. Intuitively one might feel the need  
for such an interdependence, but the data we  
present here show that past studies have not  
delineated it. We have also shown [O'Brien,  
1971] the extreme uncertainties involved in  
deducing characteristics of auroral electrons  
from ground-based studies.

#### CONCLUDING COMMENTS

Far from clarifying the cause and source of  
auroral electrons, the additional unique capa-  
bilities of the Twins 2 experiments have served  
to show that no single theory known to us  
satisfies all the observations. However, we find  
that a potpourri of several theories can ex-  
plain the data, if we considerably modify each  
model.

Thus, if we invert the sense of the plasma  
instabilities visualized by Perkins [1968], we  
might explain only the field-aligned bursts. If  
we allow the magnetic-field lines through the  
aurora generally to close in the plasma sheet

but frequently to meet interplanetary-field lines in the magnetosheath [see Dungey, 1968], we can explain the continuum and its replenishment, given weak diffusion by wave-particle interactions [Kennel, 1969] to precipitate it.

To provide the auroral-electron peak with a few kiloelectron volts, we need either strong diffusion, acceleration in a very disordered Taylor-Hones model field, or both of these.

Finally, to explain the pitch-angle distribution of low-energy electrons (40–100 ev), we need a parallel electrostatic field at high altitudes with a potential drop of the order of 40 volts.

Such a post hoc mixture of the various models is aesthetically far from attractive and scientifically very unsatisfactory. It is possible that it can be replaced by a new unified theory. We wish to emphasize, however, that every individual finding of our experiment is substantiated by other experiments, and we have brought the whole together with the Twins 2. Therefore, any postulated source mechanism must be capable of simultaneously producing electron fluxes of the nature outlined here. We regard it as most likely that there are two or more mechanisms involved, although whether there are the five or six mechanisms discussed above is not clear, nor is the extent to which these processes are coupled or uncoupled clear. These uncertainties remain a matter for further study.

#### APPENDIX.

*Search for possible spurious effects.* It is clear from the exact relationship of the modulation of counting rates and the magnetometer orientation that the large modulations of Figures 2, 3, and 8 must arise from a peculiar property of each payload. The fact that, when the sporadic effect is seen in one payload, it is seen in the other implies that the auroral radiation must be different at those times. For reasons given in the text, we judged that, when the modulation is present, it is caused by the off-axis fan-shaped response of the DED sensor sweeping in and out of an abnormally large flux of electrons with pitch angles  $\alpha \lesssim 10^\circ$ . Here we examine the following other possible explanations:

1. 'Stray' electrical or magnetic fields in the payloads.

2. Malfunction of the DED's.
3. Saturation effects in any sensor.
4. Spurious counts from any of several sources, e.g., corona, pulse-code-modulation bit errors.
5. Interaction of one payload with the other.
6. Modulation of the ambient auroral electrons by the transmitted and modulated RF power ( $\sim 5$  watts).
7. Peculiar shielding of the sensors by 'stray' material or by a particular payload configuration.
8. 'Background' radiation or protons.
9. Acceptance of lower- or higher-energy electrons.
10. Periodicities in the auroral fluxes at small pitch angles.

We find that none of these causes can possibly give rise to the observed effects. If the enhancements were due to any of the possible causes numbered 1 through 6, a spurious effect would be required to be consistently in synchronization with the payload spin rate. We cannot conceive of such a fortuitous circumstance. We can further assert that no stray material was intermittently shielding the detectors (possible cause 8), since the absence of coning showed that the payloads maintained their structural integrity after separation. Contamination from intense fluxes of particles outside the energy passbands of the DED's can be discounted because the other particle detectors would have detected such fluxes. Finally, if the effects were due to natural periodicities in the incident electron flux at small pitch angles, the periodicities would have to lie in phase with the individual payload spin rates, a highly unlikely possibility. We therefore conclude that our original interpretation is correct.

*Acknowledgments.* The number of personnel to whom we are grateful is extremely large, but we are very happy to thank Dr. A. Opp and Mr. J. Holtz for their support for the challenging Twins concept, Mr. N. Peterson of Goddard Space Flight Center and the personnel of Churchill Rocket Range for launch support, and Space Craft, Inc., for technical support. Dr. L. Westerlund, Mr. J. Sneddon, Mr. F. Abney, and Mr. R. Harrison were extremely helpful in all phases of the project.

Analysis of the data was supported by the Science Foundation for Physics of the University of

Sydney. The Twins were  
University under  
the National Aeronautics  
Administration.

The Editor thanks  
Mozzer, and B. A. Whal  
evaluating this paper.

#### REF

- Axford, W. I., *Magn  
Magnetospheric Phys  
Richmond, Virginia.*
- Bame, S. J., J. R. A.  
E. W. Hones, and I  
of the plasma sheet  
*J. Geophys. Res.*, 72,  
Belon, A. E., J. E. F  
Mather, N. W. Gla  
jugacy of visual au  
quiet periods. *J. Ge  
Chamberlain, J. W.,  
Airglow, Academic,  
Chamberlain, J. W.  
auroral particles, R  
461, 1969.*
- Chappell, C. R., *The  
trons with the at  
University, Houston*
- Dungey, J. W., *The  
magnetosphere, in  
edited by B. M. M.  
York, 1968.*
- Eather, R. H., Sh  
O. I., *J. Geophys. J*
- Eather, R. H., and  
polar-cap aurora:  
1969.
- Evans, D. S., Low  
tion using the co  
tipplier, *Rev. Sci.*
- Evans, D. S., Ro  
electron precipit  
X-611-66-9, Go  
Greenbelt, Md.,
- Evans, D. S., Ro  
auroral electron  
by B. M. Mc  
York, 1967a.
- Evans, D. S., A  
tation of aurora  
72, 4281, 1967b
- Frank, L. A., O  
electrons and  
sphere, in *En  
by B. M. M.  
1968.*
- Hoffman, R. A.,  
electron burst  
Ogo 4, *J. Geo*

Sydney. The Twins were developed and built at Rice University under contract NASr-209 with the National Aeronautics and Space Administration.

\* \* \*

The Editor thanks I. B. McDiarmid, F. S. Mozer, and B. A. Whalen for their assistance in evaluating this paper.

# REFERENCES

- Axford, W. I., Magnetospheric convection, in *Magnetospheric Physics*, p. 421, William Byrd, Richmond, Virginia, 1969.
- Bame, S. J., J. R. Asbridge, H. E. Felthaus, E. W. Hones, and I. B. Strong, Characteristics of the plasma sheet in the earth's magnetotail, *J. Geophys. Res.*, **72**, 113, 1967.
- Belon, A. E., J. E. Maggs, T. N. Davis, K. B. Mather, N. W. Glass, and G. F. Hughes, Conjugacy of visual auroras during magnetically-quiet periods, *J. Geophys. Res.*, **74**, 1, 1969.
- Chamberlain, J. W., *Physics of the Aurora and Airglow*, Academic, New York, 1961.
- Chamberlain, J. W., Electric acceleration of auroral particles, *Rev. Geophys. Space Phys.*, **7**, 461, 1969.
- Chappell, C. R., The interaction of auroral electrons with the atmosphere, Ph.D. thesis, Rice University, Houston, Texas, 1968.
- Dungey, J. W., The reconnection model of the magnetosphere, in *Earth's Particles and Fields*, edited by B. M. McCormac, Reinhold, New York, 1968.
- Eather, R. H., Short-period pulsations in 6300 Å, *J. Geophys. Res.*, **74**, 4908, 1969.
- Eather, R. H., and S. Akasofu, Characteristics of polar-cap auroras, *J. Geophys. Res.*, **74**, 4794, 1969.
- Evans, D. S., Low-energy charged-particle detection using the continuous channel electron multiplier, *Rev. Sci. Instrum.*, **36**, 375, 1965.
- Evans, D. S., Rocket observations of energetic electron precipitation in the auroral zone, *Ser. X-611-66-9*, Goddard Space Flight Center, Greenbelt, Md., 1966.
- Evans, D. S., Rocket observations of low-energy auroral electrons, in *Aurora and Airglow*, edited by B. M. McCormac, Reinhold, p. 191, New York, 1967a.
- Evans, D. S., A 10-cps periodicity in the precipitation of auroral-zone electrons, *J. Geophys. Res.*, **72**, 4281, 1967b.
- Frank, L. A., On the distribution of low-energy electrons and protons in the earth's magnetosphere, in *Earth's Particles and Fields*, edited by B. M. McCormac, Reinhold, New York, 1968.
- Hoffman, R. A., and D. S. Evans, Field-aligned electron bursts at high latitudes observed by Ogo 4, *J. Geophys. Res.*, **73**, 6201, 1968.
- Kennel, C. F., Consequences of a magnetospheric plasma, in *Magnetospheric Physics*, William Byrd, Richmond, 1969.
- Lampton, M., Daytime observations of energetic auroral-zone electrons, *J. Geophys. Res.*, **72**, 5817, 1967.
- Lampton, M., R. Albert, K. A. Anderson, and I. M. Chasc, Rocket observations of charged particles in the auroral zone, paper presented at Birkeland Symposium, Sandefjord, Norway, 1967.
- Montgomery, M. D., Observations of electrons in the earth's magnetotail by Vela launch 2 satellites, *J. Geophys. Res.*, **73**, 871, 1968.
- O'Brien, B. J., Lifetimes of outer-zone electrons and their precipitation into the atmosphere, *J. Geophys. Res.*, **67**, 3687, 1962.
- O'Brien, B. J., High-latitude geophysical studies with satellite Injun 3, part 3, Precipitation of electrons into the atmosphere, *J. Geophys. Res.*, **69**, 13, 1964.
- O'Brien, B. J., Interrelations of energetic charged particles in the magnetosphere, in *Solar Terrestrial Physics*, edited by J. W. King and W. S. Newman, pp. 169-211, Academic, New York, 1967.
- O'Brien, B. J., Considerations that the source of energetic auroral particles is not a parallel electrostatic field, *Planet. Space Sci.*, **18**, 1821, 1970a.
- O'Brien, B. J., Auroral electron characteristics deduced from ground-based observations, *J. Atmos. Terr. Phys.*, **33**, 679, 1971.
- O'Brien, B. J., F. Abney, J. Burch, R. LaQuey, R. Harrison, and T. Winiecki, Specs, a versatile space-qualified detector of charged particles, *Rev. Sci. Instrum.*, **38**, 1058, 1967.
- Perkins, F. W., Plasma wave instabilities in the ionosphere over the aurora, *J. Geophys. Res.*, **73**, 6631, 1968.
- Piddington, J. H., The magnetospheric radiation belt and tail plasma sheet, *Planet. Space Sci.*, **16**, 703, 1968.
- Riedler, W., Messung der Energiespektren und Winkelverteilungen von Elektronen im Nordlicht, *Rep. 663*, Kiruna Geophys. Observ., Kiruna, Sweden, 1966.
- Sonnett, C. P., D. S. Colburn, and R. G. Currie, The intrinsic magnetic field of the moon, *J. Geophys. Res.*, **72**, 5503, 1967.
- Speiser, T. W., Particle trajectories in a model current sheet, based on the open model of the magnetosphere, with applications to auroral particles, *J. Geophys. Res.*, **70**, 1717, 1965.
- Speiser, T. W., Particle trajectories in model current sheets, 2, Application to auroras using a geomagnetic tail model, *J. Geophys. Res.*, **72**, 3919, 1967.
- Taylor, H. E., and E. W. Hones, Jr., Adiabatic motion of auroral particles in a model of the electric and magnetic fields surrounding the earth, *J. Geophys. Res.*, **70**, 3605, 1965.

ED's.  
any sensor.  
n any of several  
se-code-modulation

load with the other.  
ambient auroral elec-  
and modulated RF

f the sensors by  
particular payload

n or protons.  
or higher-energy

auroral fluxes at

se causes can pos-  
served effects. If the  
any of the possible  
6, a spurious effect  
consistently in syn-  
oad spin rate. We  
fortuitous circum-  
sert that no stray  
shielding the de-  
since the absence  
payloads maintained  
er separation. Con-  
ves of particles out-  
of the DED's can  
other particle de-  
ed such fluxes. Fi-  
re to natural perio-  
electron flux at small  
ies would have to  
idual payload spin  
ssibility. We there-  
ginal interpretation

umber of personnel  
extremely large, but  
Dr. A. Opp and Mr.  
for the challenging  
on of Goddard Space  
sonnel of Churchill  
support, and Space  
port. Dr. L. Wester-  
F. Abney, and Mr.  
helpful in all phases

upported by the Sci-  
of the University of

S278

O'BRIEN AND REASONER

Westerlund, L. H., Rocket-borne observations of the auroral electron energy spectra and their pitch-angle distribution, Ph.D. thesis, Rice University, 1968.

Westerlund, L. H., The auroral electron energy spectrum extended to 45 ev, *J. Geophys. Res.*, 74, 351, 1969.

Winiecki, T. C., Analysis of rapid temporal fluctuations in auroral particle fluxes, M.S. Thesis, Rice University, Houston, Texas, 1967.

(Received November 5, 1970;  
accepted August 20, 1971.)

WE

A Nike-T particles from Churchill aligned current and represent changes in enhancement and increase for auroral measured had an energy order of magnitude the luminous aurora from north of the tail in the tail the north to thread the electrical of luminous direction be a space sphere to rocket d

Auroral caused by the magnetosphere [Alfvén] a direct measurement through auroral fluxes of low energy 10 keV. M. H. Rees published the auroral spectrum. Albert, 1962. Ground-based observations (bays) are overhead auroral spherical flowing v

Copyright